# Insulated Solar Electric Cooker

by

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2020

## Statement of Disclaimer

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## List of Nomenclature

| | |
|---|---|
| BOM | Bill of Materials |
| COVID-19 | Coronavirus Disease 2019 |
| DAQ | Data Acquisition System |
| DVPR | Design Verification Plan and Report |
| IPC | Institute of Printed Circuits |
| ISEC | Insulated Electric Cooker |
| MPI | Manufacturing Process Information |
| NiCr | Nichrome |
| NPT | National Pipe Thread |
| OEM | Original Equipment Manufacturer |
| PCM | Phase Change Material |
| PDH | Peak Diode Heat |
| POD | Power Optimization Device |
| PRINCE | Promoters, Researchers and Innovators in New and Clean Energy |
| PV | Photovoltaic |
| QFD | Qualifications for Design |

## Executive Summary

The purpose of this Final Project Report is to highlight the work completed by the interdisciplinary engineering capstone project for the Insulated Solar Electric Cooker (ISEC) at California Polytechnic State University, San Luis Obispo under the supervision of Professor Jim Widmann (Mechanical Engineering) and Dr. Peter Schwartz (Physics). Dr. Schwartz, better known as Pete, has been working on the project with a team of students for the past five years and is working to integrate the ISEC in Ghanaian communities. This project focuses on making the ISEC mass-manufacturable and making the transition from biomass cooking to solar cooking as familiar as possible. Our concept chosen is called the Sugar Oven, which has been designed to optimize and simplify usage to be an inexpensive and easy alternative to biomass cooking. The design we chose will also feature a standardized manufacturing process and reduces risk of injury. This report features the calculations for the thermal conductivity and thermal battery and addresses the possible risks of diode failure. It also will cover the best materials to build the Sugar Oven. Due to the current nature of COVID-19, the planned building, testing, and analysis could not be done. This report instead will cover how to build the sugar oven and detailed descriptions of the tests that need to be conducted. It will lastly touch base on further research and work that can be done in furthering the development of our design.

# 1 Introduction

## 1.1 Sponsor Background and Needs

To this day, around a third of the world's population still relies on the usage of biomass fuel for cooking. Not only is this a health risk, it directly contributes to the earth's increasing temperature and deforestation. The lack of ventilation in homes and the excessive buildup of carbon and silica emissions and particles leads to lung disease. Biomass fuels have been revealed to be linked to low birth weights, nutritional deficiency, tuberculosis, and other respiratory illnesses [1].

Pete began working on the ISEC in 2015 with a small group of volunteer students, first learning about the development of solar energy and how to effectively cook with it. Since then, its design has been developed and studied by volunteer students, physics classes in special problems and independent studies.

## 1.2 Formal Problem Definition

The goal of the ISEC is to create a clean cooking alternative to biomass cooking, which has been linked to long-term health and environmental problems. Despite its development in the past few years, the most recent ISEC design lacks a formal bill of materials and lacks a repeatable manufacturing plan. Our project focuses on creating an ISEC prototype that can be scaled for manufacturing, is compliant with the manufacturing specifications, and remains low-cost for user purchase in Ghana.

These engineering requirements are highlighted in Table 1.

*Table 1. Formal Engineering Requirements.*

| Spec. # | Parameter Description | Requirement or Target | Tolerance | Risk | Compliance |
|---|---|---|---|---|---|
| 1 | Size of Panel | Panel: $47 \times 21.3 \times 1.4\ in$ | ±0.005 | Medium | I, S |
| 2 | Size of Thermal Battery | Pot: $12\ Ø\ x\ 10\ in$ | ±0.005 | Medium | I, S |
| 3 | Size of Concrete and Perlite Insulation | Pot: $24\ Ø\ x\ 18\ in$ | ±0.005 | Medium | I, S |
| 4 | Size of Pot | Pot: $9.5\ Ø\ x\ 11\ in$ | ±0.005 | Medium | I, S |
| 5 | Production Cost | $160.00 | Maximum | High | S |
| 6 | Power | 100 W | Maximum | High | A, T, I, S |
| 7 | Thermal Contact Heat Loss | $<20$ % heat loss | Maximum | High | A, T, I, S |
| 8 | Insulated | $<$ 5% heat loss | ±5% | High | A, T, I, S |
| 9 | Food Safe | No contamination | None | High | T, I |
| 10 | Cookability | The cooking process should remain like traditional cooking methods in Ghana | ±5 min | High | T, I |

## 1.3 Objective and Specification Development

Our objective is to create a robust, mass-manufacturable insulated solar electric cooker (ISEC) capable of meeting the needs of a Ghanaian community. The ultimate, long-term goal of the greater project is to implement the ISEC into as many developing countries who still use biomass fuel as their main cooking method. To boost local economies, all ISECs will be manufactured locally and with as many locally sourced parts and supplies as possible. The formal customer requirements prioritize making the transition from using a pot over an open flame to using the ISEC as seamless as possible. We aim to create an ISEC that allows for a familiar and uncomplicated experience, is intuitive to use, and is easy to clean.

The organizations investing and donating to the project also require that the solar cookers need to be low cost for them to be able to be implemented in as many communities as possible. They also require that the cookers do not release any harmful emissions.

## 1.4 Project Management and COVID-19 Adjustments

Fall quarter was dedicated to planning the project and creating a concept for our prototype. It started with planning deadlines and deliverables, as well as establishing a timeline for our project. With deadlines set, we began brainstorming ideas and eventually narrowing down our design concepts using a Pugh matrix. Winter quarter was dedicated to expanding on our chosen concept and evaluating the design. This included an in-depth analysis and calculations to evaluate our design and ensure it met the project specifications. Near the end of the quarter, we had ordered components and manufactured the electrical subsystem, but were unable to complete testing.

Due to COVID-19, Cal Poly's campus went completely virtual starting in March of 2020 and continuing until the end of the school year. During Spring quarter Cal Poly closed its campus and our group did not have access to our sponsor's on-campus lab or the machine shops. This inhibited our group's ability to continue on with manufacturing and testing the prototype. To compensate, we have included in this report detailed manufacturing and testing plans to complete the prototype that was designed. Also included are suggestions and recommendations to account for potential variations in the resulting product.

# 2 Background

## 2.1 Existing Products

Currently, no other solar electric cooker on the market utilizes the same phase change technology in conjunction with diodes and a PV panel, which makes our ISEC unique. The most common technology that models solar electric cooking is made for camping and is used for slow cooking; these devices are not designed for long term, everyday use. Such a model is shown in Figure 1 and shows a box model.

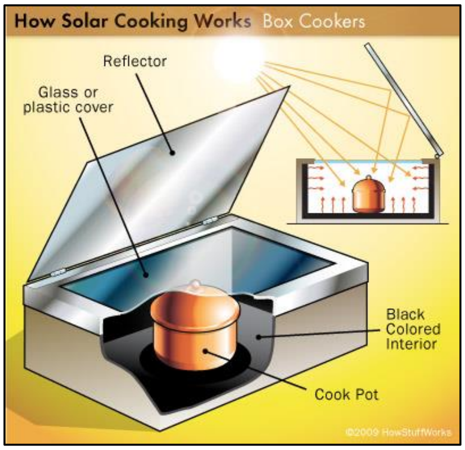


*Figure 1. HowStuffWorks Solar Cooker Box Model.*

Pete also works in collaboration with other companies around the world who take a different approach to solar cooking – by using parabolas. Two of his contacts are Crosby Menzies, founder of SunFire in South Africa, and Ajay Chandak, who founded PRINCE (Promoters, Researchers and Innovators in New and Clean Energy) in India. Parabolic cookers reflect and focus the sunlight into one focal point at the bottom of the pot. This method of cooking allows the pot to reach temperatures high enough to bake bread and fry food [2].

*Figure 2. Parabolic Solar Cooker manufactured by PRINCE India [3].*

Despite the Sugar Oven's unique design, there are other solar cooking models in the world that partly resemble ISEC according to Unger, et al. The design most similar to the mechanical engineering team prototype is a Solar Box Cooker with PCM Thermal Storage. This design includes a concentric pot model but uses a mixture of nitrite and nitrate salts as the phase change material. The use of erythritol was the result of another solar cooking model, Evacuated Tube Solar Cooker with PCM. The difference between this model and ISEC prototypes is the use of evacuated tube solar heat, instead of PV panels. The last similar model is the Domestic Electric cum Solar Oven, although this model uses technology from the solar cooker box model, in which reflective panels are used to increase solar intensity, in conjunction with an external electricity source [4].

## 2.2 Current State of the Art

In 2017, under Dr. Schwartz's supervision, a volunteer group of students wrote the publication Insulated *Solar Electric Cooking - Tomorrow's Healthy Affordable Stoves*. It proposes a cooker where a solar panel directly connects to an electric heater with an insulated chamber. The end-product is a $100 prototype that was then implemented in Uganda. These preliminary models were organized into three categories: barbeque, a concrete thermal storage container, and a boil-and-simmer cooker. After initial testing, one of the main discoveries is the need to clamp wires together, as opposed to soldering, to avoid melting during cooking. They also discovered that the resistance to the heating element is vital to maximizing its power, and that the performance improves if the solar panel can be moved at least once a day to track the sun. The initial prototype used the earth and straw as insulation. Other ideas included rooting the cooker in the ground to act as a natural insulator, which was quickly prohibited for cultural reasons. The pot was also made with stainless steel and incorporated the use of NiCr wire. The final prototype was then brought to Ghana. The community disliked the initial appearance and noticed that the solar panels provided insufficient power to cook in the evening after returning from working at the farm. They instead used the ISEC to slow-cook beans throughout the day and to keep food warm [5].

Another independent study, conducted by Cal Poly general engineering undergraduate student Matt Walker during Winter 2019, addresses using the ISEC as a makeshift oven. He explores the possibilities of baking bread by testing for efficiency of energy over time. His work led to the discovery of better placement of the diodes, as little heat travels upwards. He also brings up the point of eliminating fiberglass as an insulator [6]. This study is also shown in the video "Baking Bread in the sleeved ISEC", as listed in the ISEC research website. During this study, improvements to the diodes and the solar panels were also made compliant with its respective factory documentation [7]. The diode factory requirements are listed by DC Components Co., Ltd. [8] and the solar panels meet the specifications of Grape Solar [9]. The diodes are low-cost, low leakage, and high-performing and are accessible in Ghana. The specifications highlight their maximum performance in a graphical manner. The solar panel specifications highlight a 5-year warranty, along with clarifying dimensions and electrical usage.

In the paper *Hot Diodes! Dirt Cheap Cooking and Electricity for the Global Poor?* the proposed design eliminates the use of the NiCr wire and adopts the use of heating the ISEC with diodes. This makes the usage of electric cooking cost competitive with biomass cooking [10].

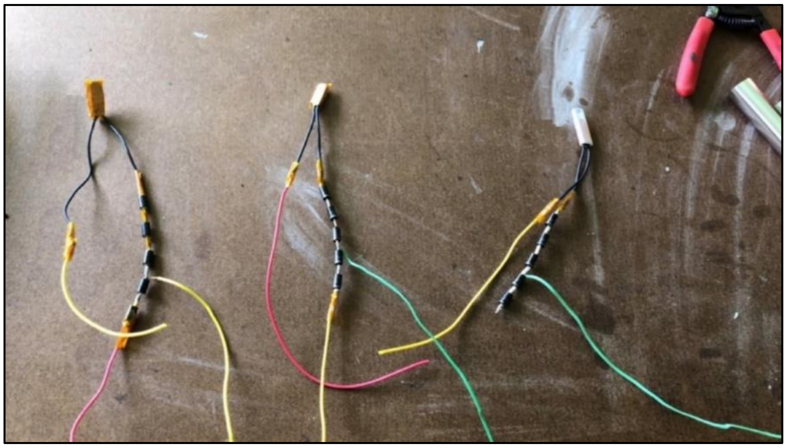

*Figure 3. Initial Diode Chain Prototype.*

Over the summer of 2019, Dr. Schwartz and some of his students visited Ghana to implement their newest model of the ISEC. This trip helped the group understand their end-user better and helped with the development of the manufacturing process. The group also met with a company that will be manufacturing the pots used in the building of the ISEC. The trip also allowed them to test the ISEC in the environment they will be used in.

As mentioned before, there have been several iterations of the solar electric cooker under the direction of Dr. Schwartz. The previous ISEC iterations can be separated into two categories, with and without thermal storage. The first prototype is known as the barbeque model and includes a 5-gallon steel drum, surrounded by insulation, inside of a 55-gallon plastic drum. The heater of this model comes from an electrically powered burner thermally connected to the lid of the cooking chamber. The next prototype, the Concrete Thermal Storage model, utilized solar electricity to heat a concrete block, mainly to be used for frying, grilling, and baking. The last prototype that falls within the category of without thermal storage, is the Boil and Simmer prototype. This prototype includes an immersion heater, where the electrical heater is enclosed in stainless steel tubing and connected to the lid to be placed into the food [5].

The most recent prototype tackles the problem of using the ISEC when there is no sunlight, such as when a family is cooking at night. This prototype uses the idea of cooking with phase change thermal storage, using the artificial sweetener erythritol as the phase change material (PCM). In addition to our senior project, current problems the project group are tackling are the issues with corrosion and finding a high-temperature soldering alternative. The first exploration of thermal storage utilized NiCr wire within a concrete block. There were many iterations of this specific design, since many of the prototypes resulted in a fire [4]. The thermal storage was not improved upon until a mechanical engineering senior project group took on the task. This was the point at which erythritol was selected as the PCM for the thermal storage. This ISEC prototype utilized a chain of 22 diodes as the heating element immersed in the PCM. Our Sugar Oven concept uses this ISEC prototype as the starting point, utilizing diode heating and erythritol as the PCM.

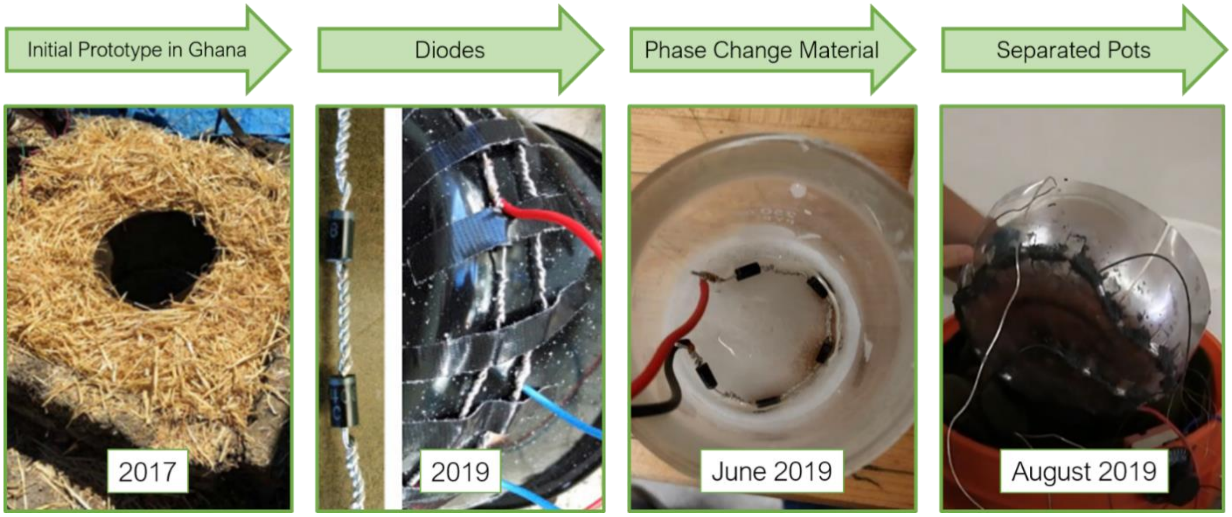


*Figure 4. ISEC Prototype Progression.*

Dr. Schwartz is currently overseeing a senior project that is reinvestigating the usage of wire as resistive heating instead of diodes as the heating element. They are currently working in conjunction with a group in the United Kingdom to optimize the performance in getting power from the solar panel into heating food. This Power Optimization Device (POD) was created to maintain the voltage from the solar panel throughout the day and extract the maximum current from the panel. This idea was presented to our group this quarter by Dr. Schwartz as an alternative to diodes, but it was decided to continue with the diode heating element we were already designing due to the length of time allotted for this project and based on where the resistive heating project is in the development process.

## 2.3 Specific Technical Data and List of Applicable Standards

Previous ISEC prototypes do not strictly follow any manufacturing standards. In order to improve upon the diode heating element design, our project will be utilizing the IPC J-STD-001 standard for soldering and assembling electrical components. This standard provides guidelines for producing high quality soldered interconnections. The purpose of this is to increase electrical conductivity between parts and will utilize JB Weld to increase thermal conductivity to the PCM, while also highly insulating electrical conductivity between the diode leads and the phase change assembly [11].

# 3 Design Development

## 3.1 Discussion of Conceptual Designs

Conceptual development revolved around the ideals of making the technology "invisible". Adoption issues from previously introduced technology has stemmed from the issue of having to learn to use the technology. A possible example of this is having to learn how to operate an iPhone using only one button or no buttons. With this guiding principle of "minimally invasive technology" in mind, several concepts were developed: The Model 3, the Rice Cooker, the Flange ISEC, and the Sugar Stove, now renamed to Sugar Oven.

Model 3 was the working prototype we began our testing with. The detailed sketch of Model 3 shown in Figure 5 is the manufactured version, which would have been built out of sheet metal bent into a cylindrical shape and welded together. Our prototype was a jury-rigged version consisting of two pots, serving as a proof of concept. This mode was not ideal, as usage led to many consumer-adoption issues. Primarily, the unwieldiness of a very hot and heavy pot with wires attached made it frustrating to use day to day.

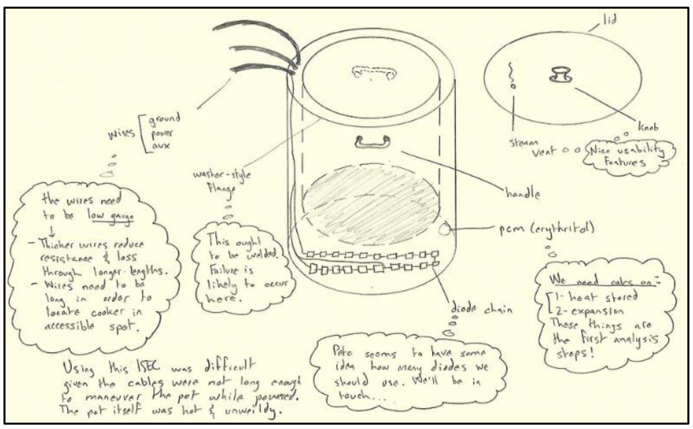


*Figure 5. Detailed Sketch of the Model 3.*

The Rice Cooker concept aims to increase the surface area and heat transfer from the phase change material to the pot. This can be observed by the sloping surface of the pot, creating a wok-style pot.

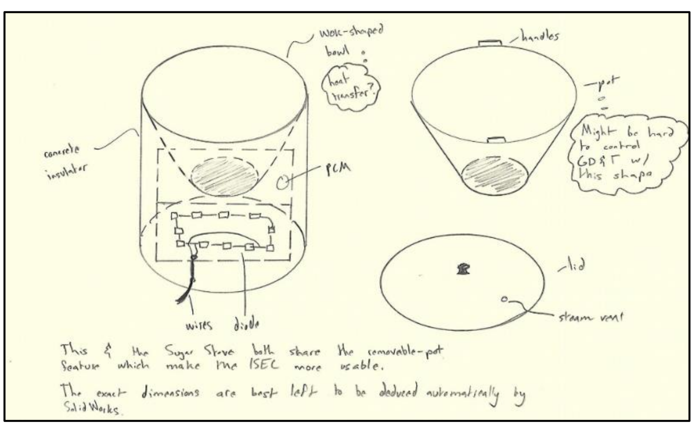


*Figure 6. Detailed Drawing of the Rice Cooker Concept.*

The Flange ISEC (shown in Figure 7) is one of the conceptual models developed that was designed to remedy this unwieldy design. The PCM portion of the ISEC serves as a base, which a flanged pot then locks into. This concept would eliminate the need to dodge wires or lug around a very heavy phase change assembly.

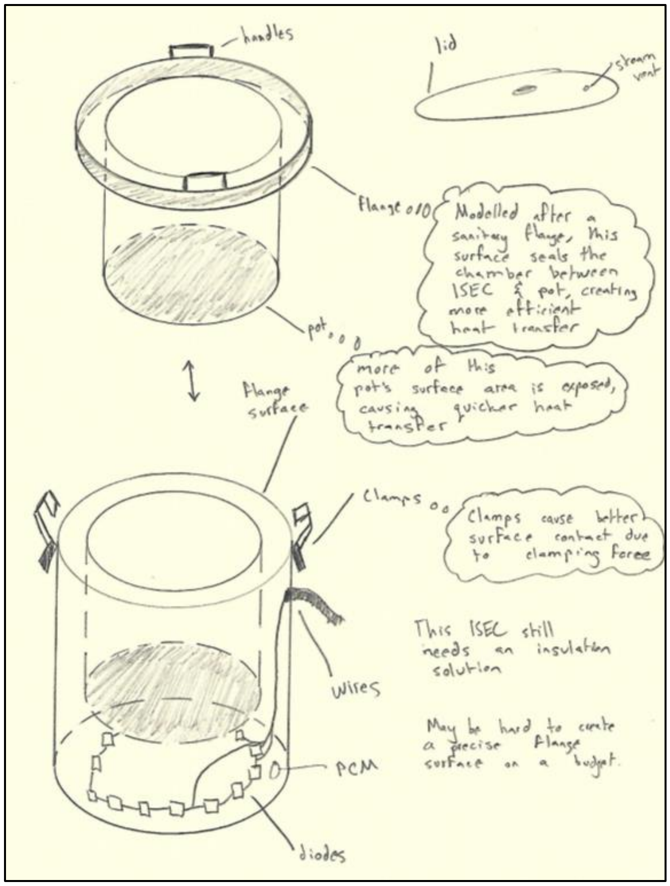


*Figure 7. Detailed Drawing of the Flange ISEC.*

The concepts discussed each had pros and cons that were then outlined in a Pugh Matrix (Table 2 in Appendix B). After exhausting all possible options, the group decided on a model we call the Sugar Oven (formerly known as the Sugar Stove).

## 3.2 Concept Selection

Ultimately, the concept selected was the sugar stove – although our design now functions more like an oven and has a cylindrical design. This design features a heavily insulated phase change assembly, referred to frequently as a "thermal battery". The idea behind this design was to focus on using the currently captured heat more efficiently rather than add more power. Insulation was a key factor that had not been factored into prior studies.

## 3.3 Supporting Preliminary Analysis

Our preliminary analysis calculations and code can be found in Appendix F, which explains the details that support our analysis. The largest part of the analysis is the heat transfer, because the system needs enough heat to thoroughly cook a meal. It also needs to direct a majority of the heat through the food to cook it. Knowing this, we calculated the energy stored in the erythritol.

After doing this, we needed to consider the ISEC in several state conditions:

1. The Stray Heat Model, which looks at the housing with the battery at 140℃.
2. The Initial Load Operation Model, which looks at the pot at 15℃.
3. The Steady State Operation Model, which looks at the pot at 100℃.

The system we want to utilize is too complex to be modeled with the lumped capacitance method, and transient analysis would require too many nodes to be accounted for. Instead, by performing state analysis, we can “unfold” our battery and analyze the system with one-dimensional heat transfer.

The biggest design challenge in the heat circuit is that we need to reduce the resistances ($R_{cond,\ conv,\ rad}$) to direct heat through the pot. This design can be improved by increasing the emissivity of the pot and the heating surfaces of the battery. It may also be improved through the use of thermal grease or contact filler on the bottom of the pot.

In this analysis, we will assume the anodized aluminum to maximize $\varepsilon$ (emissivity), which will minimize $R_{rad}$. Anodizing the aluminum will be a major manufacturing step. It is also an important consideration to have a smoothness tolerance on the inner surface area of the pot to minimize contact resistance ($R_{cond}$).

Looking at the expansion and pressure analysis, we created a table that outlines the mass, the maximum volume, the change in volume, and the change in pressure of the phase change material and how it changes with the number of meals. The maximum pressure is calculated by taking $(\Delta V)(1.5)$ and using this volume as air under the ideal gas law. These calculations showed that the battery will experience pressure cycles. To enhance the longevity of the battery, our group decided to add a breather vent to this model.

After calculating these numbers, we verified our findings over MATLAB. These verifications can also be found in Appendix F.

# 4 Description of the Final Design

## 4.1 Overall Description and Layout

Our natural design process led us to an ISEC configuration more like an oven, rather than a singular pot. There is a *lot* to be said about what we learned during our time with power tools and cookware, but the main lesson was that the focus on manufacturing these ISECs for further testing and experimenting is repeatability. Most of the problems we saw from our perspective was the inability to recreate consistent prototypes. The final design focuses on two critical design principles:

1. The system must be easy to manufacture consistently.
2. The system should focus on redirecting heat instead of adding more.

We accomplished the first step by creating a design calculator, CAD models, a manufacturing plan, and a testing plan. These steps alone were a lot of progress, because up until this point ISECs had been creatively jury-rigged using household pots. This is that very first transition from prototype to true manufacturing. Our MATLAB design script will also be helpful during the manufacturing of this prototype, as it can be used to quickly resize geometries and observe what effect changing certain parts of the design should have. Unfortunately, due to COVID-19 restrictions, we were unable to refine these materials through hands on experience and validate our design calculations script; however, plenty of research and thought has been put into revisions of the plan during spring quarter.

The second step is the trickier of the two. All three forms of heat transfer—conduction, convection, and radiation—heat transfer through a phase change material, and all three states of matter are present. The heat transfer calculations required to fully understand exactly what is going on in the battery are far too complex for an undergraduate, instead, we've made engineering assumptions and simplifications (one such example is treating the battery as a control volume) to proceed with the best of our abilities. The driving design feature to direct heat within the ISEC system is the insulation. Our final design is shown in Figure 8. More detailed drawings of the components can also be found in Appendix C.

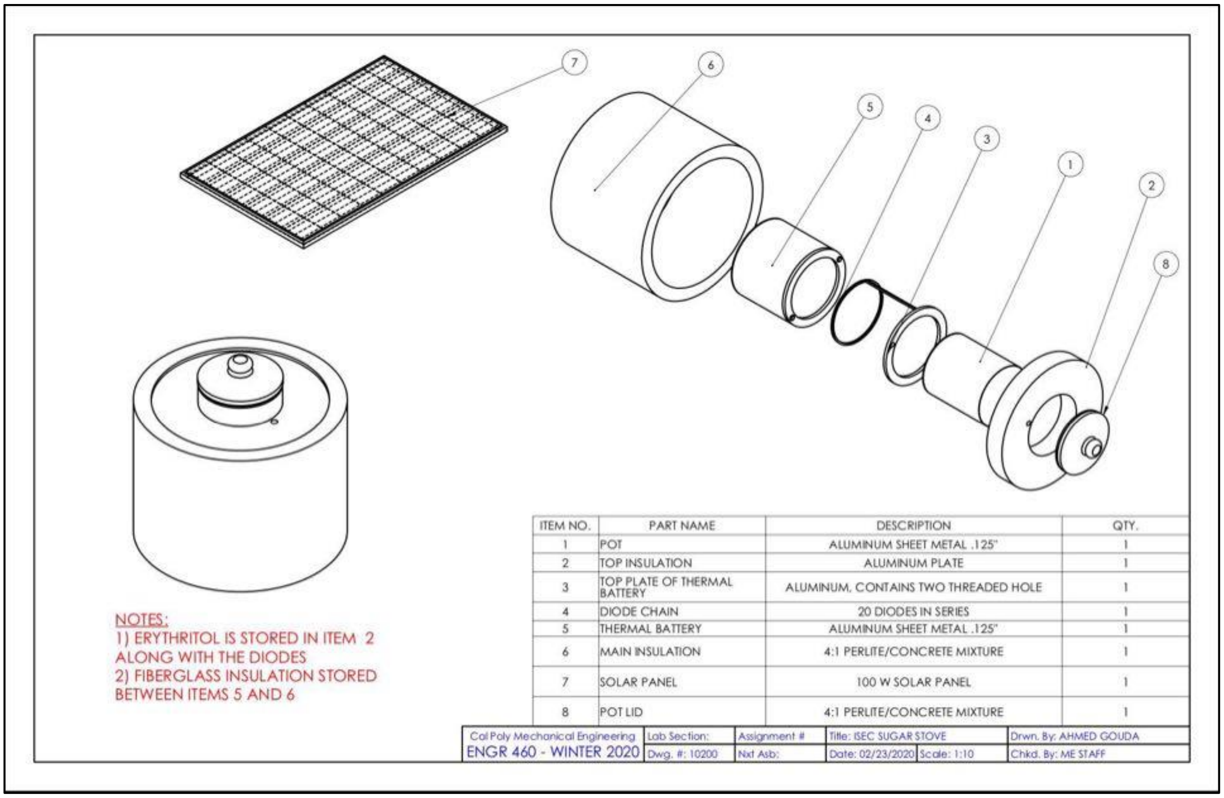


*Figure 8. The Sugar Oven Assembly.*

## 4.2 Detailed Design Description

The overall design of the ISEC revolves around 4 subsystems: the electrical system, the thermal battery and PCM, the insulation, and the structural system. Details of each subsystem are highlighted in the following sections.

### 4.2.1 The Electrical System

The electrical system has two primary components: the solar panel and a chain of connected diodes acting as the heating element for the ISEC. The chain consists of 16 diodes to account for the solar panel voltage and for an even voltage drop across each diode. Each diode will be connected to the next using copper wire, with the leads then encased in JB Weld; this is in accordance with IPC standards. The diode chain is completed with a 2-pole connector set which allows for easy connect/disconnect from the solar panel (power source) to the oven. A schematic of the electrical system can be found in Figure 9.

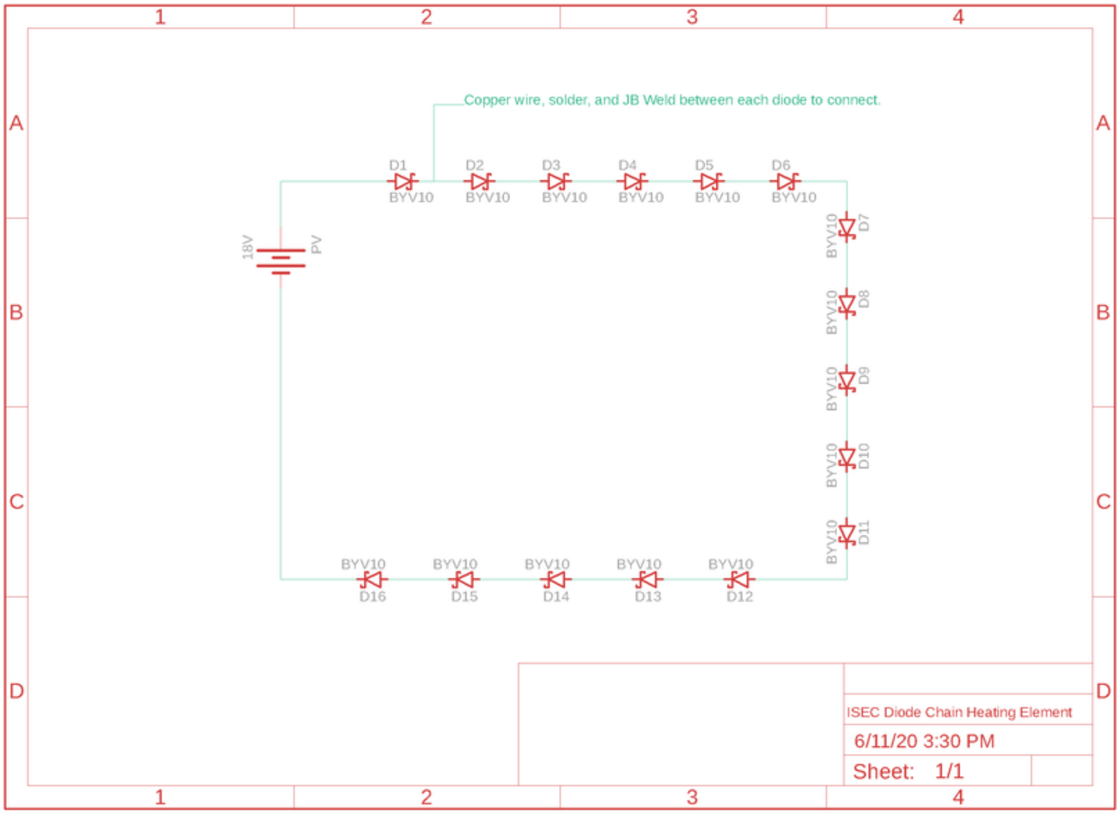


*Figure 9. ISEC Diode Chain Heating Element Schematic.*

### 4.2.2 PCM

We chose erythritol as the phase change material (PCM) that will be employed for the Sugar Oven ISEC. Erythritol has been used as a phase change material in previous iterations of the ISEC and proved to work well for the needs of the project. With a melting temperature of around 118°C and a decomposition temperature of around 160°C (depending on the grade of erythritol), the diode chain will melt sugar and store heat in the PCM [4]. Erythritol is inexpensive and accessible in Ghana, making for it to be ideal for the uses of the ISEC team. With the sugar oven design, 13.6 kg of erythritol will be stored in the thermal battery along with the diode chain. Erythritol will be poured into the thermal battery through the breather vent in the molten state.

### 4.2.3 Thermal Battery

The thermal battery and pot will both be made of aluminum, a readily available metal in Ghana. Both components are cylindrical in shape in order to streamline manufacturing. This allows for both the pot and thermal battery to be radius bent to different diameter cylinders which are then welded to base sheets cut to the same diameter. The thermal battery also contains a welded top plate containing two threaded holes for a breather vent and a plug to contain the wiring of the ISEC. This is shown in more detail in Appendix C.

The initial sizing of the battery is key—the mass of the erythritol determines how much extra energy can be stored to provide cooking performance past peak solar performance times. After determining the amount of energy required to cook one meal of soup (modeled as water for convenience) to be 2.16 MJ, this quantity was scaled by a factor of about 5.75 to provide extra power as a measure of safety against heat loss.

Pressure was unaccounted for in previous designs and was the root cause of failure for the previous prototypes. The PCM cannot be sealed within the battery due to its own expansion and the expansion of air within the battery. A pressure difference of around 440 psi was calculated through thermodynamic analysis by modeling the extra air within the battery as an ideal gas and determining its change in pressure due to temperature increase. In prior designs this pressure delta sheared the adhesive seal, compromising the integrity of the PCM enclosure and ultimately destroying the ISEC due to moisture buildup inside. To account for the volumetric expansion of the PCM, erythritol will be filled with enough extra space to accommodate this expansion and a breather vent will be installed on top of the battery to allow pressurized air to escape.

Heat transfer was a major design absence in previous prototypes. Although heat transfer within the phase change was accounted for in prior studies, the ISEC has never been designed to direct the stored energy into the pot rather than through the atmosphere. This was one of the major issues that prevented the ISEC from working functionally in our prototype trials. Contact resistance, radiation, and insulation were the primary considerations within the heat transfer design of the ISEC system. Analysis proves that insulation is the driving factor for directing heat through the pot, although other less influential factors such as pot and battery geometry have impacts as well. Emphasis on usability of our system led towards a removable pot design, as previously the thermal storage had been built into the pot. Although better heat transfer is possible with the PCM build into the pot, this design rendered the ISEC frustrating to use and unsuitable for cooking. Contact resistance and connecting the pot to the battery thermally are two of the biggest inherent challenges within our system. Two methods used to enhance this thermal connectivity will be the use of a thermally conductive powder, and the anodization of the heat battery's internal wall and pot wall. Anodization was accounted for within the heat transfer analysis however, the addition of thermally conductive powder was not. Ultimately, our heat transfer rates were calculated to a heat loss rate of about 6.5 watts, initial heat transfer rate of about 15.5 watts to the food, and a steady state heat transfer rate of around 9 watts.

Anodizing aluminum increases its emissivity, allowing it to radiate more heat across the air gap between the battery anchor wall and the pot wall. This reduces heat transfer resistance as the modes of heat transfer between these surfaces are primarily radiation and convection. However, the convention through the air has been modelled as conduction through a thin fluid for convenience and accuracy. Anodization must occur after the components have been shaped, as cold rolling aluminum after applying a surface finish may diminish the quality of the finish.

Instead of applying a thermal grease, which would increase heat transfer through the bottom of the battery anchor and the bottom of the pot, thermally conductive powders were elected to be used for their functionality. Thermal grease would get messy and need to be reapplied carefully, potentially introducing contaminants into the battery cavity with every insertion of the pot. Thermal powders will be less messy while providing similar heat transfer enhancements and can be easily replenished by pouring more in if necessary. This avoids the high risk of burns that reapplying thermal grease has. Two thermal powders are currently being considered. Aluminum nitride is our thermal powder of choice, as it has a thermal conductivity coefficient 285 $W/(m \cdot K)$ [12]. Zinc oxide is our secondary thermal powder as it is water insoluble (should moisture accumulation within the ISEC system become an issue) but only has a thermal conductivity of 60 $W/(m \cdot K)$ [13].

### 4.2.4 Insulation and Structure

There will be three main components of insulation for the Sugar Oven: an outer layer of insulation made of a perlite and concrete mixture to enclose the entire system, a top layer of the same material to cover the top of the thermal battery, and a layer of fiberglass between the insulation and thermal battery. Fiberglass has been used in previous models of the ISEC, and with a thermal conductivity of $0.0525\ W/(m \cdot K)$ it is highly insulating. Fiberglass is not a food-safe material; however, this was not addressed in previous models of the ISEC. The Sugar Oven addresses this issue by enclosing the fiberglass between two exterior layers of perlite concrete insulation. Perlite concrete mixture is another insulating material with a 3:2 concrete perlite mixture, the thermal conductivity is $0.53\ K \cdot W/(m \cdot k)$ [14]. The thermal conductivity decreases with a larger perlite to concrete ratio, but in turn decreases the compressive strength of the material. With the ability to pour the perlite/concrete mixture, a mold will be made and reused to streamline manufacturing. All these materials are inexpensive and readily available in Ghana which allows for them to fit the scope of the project. The last important consideration of our design was the outside temperature of the ISEC system. Analysis shows that in an atmospheric temperature of 30°C (86°F), the outside temperature will only reach about 32°C. The overall dimensions of the ISEC are convenient for use, standing approximately 3.1 feet tall and 3.3 feet wide.

## 4.3 Cost Breakdown

One of the fundamental design requirements that governs the project is the need for the ISEC to be low-cost. Each component was specifically chosen to minimize cost while still maintaining functionality of the system. All components and cost of components are detailed in Appendix D. Also included is a breakdown of scaled cost. The purpose of the scaled cost is to estimate the cost of these components if purchased at a large scale, in order to mass produce the ISEC and minimize cost. All cost analysis was done through the groups own research as well as information given from Pete and other members of the ISEC team. The cost of the aluminum sheet metal is yet to be determined; this is soon to change by contacting a distributer of sheet metal in Ghana. The current estimated cost of aluminum and erythritol was determined through research done on market prices of both in Ghana. These are the primary costs of the ISEC, so it is critical that a distributor is found for each to minimize price.

Much of the primary cost of the ISEC comes with the solar panel, which alone is $100 USD. The specific goal of the group was to have the components of the ISEC cost less than $100 without the solar panel, since this was already available to us courtesy of the larger ISEC team. The total prototype cost without the solar panel is $316.45. We acknowledge that this initial prototype cost does not meet the requirement of cost, but after a cost analysis, the ISEC at-cost would be $99.76. Both cost breakdowns can be found in Appendix D.

## 4.4 Special Safety, Maintenance, and Repair Considerations

Safety considerations were deliberated throughout the duration of the project, adjusting the scope and design considerably. Appendix K details the safety checklist employed while designing the ISEC, and Appendix H details the product user guide and maintenance of the Sugar Oven. A primary factor of concern for the ISEC group is food safety. With fiberglass involved in the insulation of the system, it became critical to not allow it to interface with the pot or contact the food within the pot. This was considered in the design by enclosing the fiberglass in two exterior layers of insulation made of a perlite and fiberglass mixture. A second safety concern for the ISEC is the heating of the ISEC. The ISEC is expected to reach extremely high temperatures, which can possibly burn users. To ensure that this does not happen, the thermal battery which contains the heating elements of the system will not be exposed to users. The pot that fits into the thermal battery will also have handles along the side which are made for users to carry. A third safety concern involves the high pressure within the thermal battery. The thermal battery contains erythritol that expands as it melts, causing a large pressure differential within the battery. To deal with that, the thermal battery contains a breather vent along the top of the ISEC to release excess pressure if needed. Lastly, the ISEC is a large metal and concrete fixture, which makes for it to be heavy to move. The ISEC is designed to stay in a fixed area and will have precautions that if it does need to get lifted, a group of people will be required to carry it.

Along with safety considerations, there are few assembly considerations that have been considered when designing the ISEC. Repair can easily be addressed by swapping batteries of ISEC systems. Each subsystem can be replaced under technician rework with quick field repairs being made on a component level. The diode chain has been the source of failure on previous models of the ISEC, so in this model adjustments were made. The diodes chosen for the Sugar Oven were specifically chosen to work within their manufactured specification. Along with this, the manufacturing of the diode chain has been streamlined to make sure the diodes are getting properly connected as to minimize risk of failure. This process includes connecting the leads of the diodes using copper wire, soldering the leads together, and JB welding them to enclose them from the outside environment. This process should minimize the corrosion issue that the diodes previously had, as well as make for the diodes to have minimal modes of failure. If the diodes are to fail, the entire system would not need to be replaced, although the thermal battery would need to. The aluminum from the thermal battery can be reused for future ISECs, and all the other components of the system can be maintained for future use. If the perlite/concrete mixture insulation were to fail on the ISEC, a mold will be available to make another mixture at little cost and with relative ease.

# 5 Product Realization

## 5.1 Manufacturing Process Information (MPI)

Because our group was unable to build a prototype, pictures of most processes will not be provided. The MPI will cover plans for building all the subsystems together. Anything marked with an asterisk (*) will require additional design development. The battery build would also be outsourced to an external manufacturing company.

### 5.1.1 Pot

| | |
|---|---|
| **Dimensions:** | 1. Cylinder<br>a. length = 6.75 inches<br>b. radius = 4.725 inches<br>2. Sheet Metal Disc<br>a. radius = 4.725 inches |
| **Instructions:** | 1. Sheet metal aluminum will be cold rolled into a cylinder with the given dimensions.<br>2. The cylinder will be placed into an anodizing bath* to increase its emissivity on the external side.<br>3. The cylinder will then be JB welded toa sheet metal disk via a fixture*, which creates the pot shape.<br>4. Locking grooves will be cut into the top of the pot using an oxygen torch. |

### 5.1.2 Battery

| **Battery Top** | |
|---|---|
| **Dimensions:** | 1. Aluminum Disc<br>a. thickness = 0.5 inches<br>b. inner radius = 4.75 inches<br>c. outer radius = 6.75 inches<br>2. Inner Disc<br>a. thickness = 0.5 inches<br>b. radius = 4.709 inches<br>c. radius (protruding keys) = 4.735 inches<br>3. 37/64 drill bit<br>4. 3/8 NPT<br>5. 18 thread/inch |
| **Instructions:** | 1. Aluminum disc will be drilled & face milled to create a disc-shaped ring with the given dimensions.<br>2. The smaller disc should be placed aside for pot-lid shaping.<br>3. Holes will be drilled and tapped for the breather vent. |

| **Anchor** | |
|---|---|
| **Dimensions:** | 1. Sheet Metal Aluminum<br>a. length = 7.25 inches<br>b. radius = 4.734 inches<br>2. Cylinder<br>a. radius = 4.734 |
| **Instructions:** | 1. Cylinder will be JB welded together down seam via fixture*.<br>2. The cylinder will be placed in an anodizing bath* to increase its emissivity (internal side).<br>3. The cylinder will then be JB welded to a sheet metal disk via fixture* to complete the anchor. |
| **Case** | |
| **Dimensions:** | 1. Sheet Metal Cylinder<br>a. length = 10.5 inches<br>b. radius = 6.766 inches<br>2. Sheet Metal Disk Fixture<br>a. radius = 6.766 inches |
| **Instructions:** | 1. Sheet metal aluminum will be cold rolled to a cylinder.<br>2. Cylinder will be JB welded together down seam via fixture*.<br>3. The cylinder will then be JB welded to a sheet metal disk via fixture* to complete the battery case. |

| **Battery Composition** | |
|---|---|
| **Instructions:** | 1. Anchor will be JB welded to the internal circumference of the battery top via fixture*.<br>2. Electrical connector will be threaded through the wire plug hole.<br>3. Electrical system will be soldered to plug leads.<br>4. Battery case will be welded to the external circumference of the battery top.<br>5. Battery will be filled with OEM erythritol through the breather vent hole.<br>6. Install breather vent.<br>7. Erythritol should be heat cycled once.<br>8. After ensuring proper function of the battery, the wire plug hole can be sealed with JB weld.<br>9. Heat cycle battery once more to ensure proper function. |

### 5.1.3 Pot Lid

| | |
|---|---|
| **Dimensions:** | 1. radius = 4.709 inches<br>2. protruding keys of radius = 4.735 inches |
| **Instructions:** | 1. The smaller disc from the battery top should be placed aside for pot-lid shaping. |

### 5.1.4 Housing

The housing contains three parts: the wall, the roof, and the lid. The concrete solution numbers used are based off the literature review *Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete*, published in ScienceDirect in 2011 [14].

| Housing Wall | |
|---|---|
| **Details:** | 1. Concrete Mixture<br>a. 40% perlite<br>b. 0.55 water and concrete mixture<br>2. Dimensions<br>a. internal radius = 18 inches<br>b. external radius = 20 inches<br>c. 1 inch thickness along inside of walls<br>d. height = 36 inches<br>e. bottom thickness = 2 inches |

| | |
|---|---|
| **Instructions:** | 1. Mix concrete solution.<br>2. Pour into proper molds.<br>3. Let set.<br>4. Presoak perlite in water for 30 minutes.<br>5. Set in mold for 24 hours.<br>6. Remove from molds.<br>7. Fill with fiberglass insulation. |
| **Housing Roof** | |
| **Details:** | 1. 40% perlite<br>2. 0.55 water/concrete mixture<br>3. Dimensions<br>a. internal radius = 8 inches<br>b. external radius = 20 inches<br>c. thickness = 2 inches |
| **Instructions:** | 1. Mix concrete solution.<br>2. Pour into proper molds.<br>3. Let set.<br>4. Presoak perlite in water for 30 minutes.<br>5. Set in mold for 24 hours.<br>6. Remove from molds. |
| **Housing Lid** | |
| **Details:** | 1. 40% perlite<br>2. 0.55 water/concrete mixture<br>3. Dimensions<br>a. radius = 8 inches<br>b. thickness = 2 inches |
| **Instructions:** | 1. Mix concrete solution.<br>2. Pour into proper molds.<br>3. Let set.<br>4. Presoak perlite in water for 30 minutes.<br>5. Set in mold for 24 hours.<br>6. Remove from molds. |

## 5.2 Electrical Process Information

The electrical process information is composed of just the diode chain.

### 5.2.1 The Diode Chain

| | |
|---|---|
| **Details:** | 1. 16 diodes<br>2. copper wire<br>   a. 2 inches in between each diode<br>   b. 30 inches for one diode chain |
| **Instructions:** | 1. Bend both stems of each diode outwards at a right angle.<br>2. Affix the diodes to helping hands, overlapping the bent parts to create a chain.<br>3. Begin wrapping the overlapping stems with the copper wire.<br>4. Pay special attention to keep the wrapping as tight as possible.<br>5. Solder the wire to the diode leads.<br>6. Apply a thick layer of JB Weld to encase the solder, wire, and diode leads. The JB Weld should not come into contact with the plastic diode casing. |
| **Pictures:** | <br>*Figure 10. Diode Chain Configuration.* |



### 5.2.2. Attaching the Solar Panel to the ISEC

| | |
|---|---|
| **Details:** | 1. solder<br>2. 15-amp push and connector set |
| **Instructions:** | 1. Solder the leads to the connector plug.<br>2. Plug the ISEC into the solar panel. |

## 5.3 How the Prototype Might Differ from the Planned Design

The sugar oven meets most of the engineering requirements set, but there is possibility that the design and the prototype may not fully translate from idea into fruition.

### 5.3.1 Recommendations for Future Manufacturing of the Design

Should the prototype differ from the planned design, our group has some suggestions as to what to try for improvements.

1. Changing the number of diodes used in the model.
2. Changing the type of wire used to wrap the connecting diodes.
3. Should cold rolling the sheet metal for the pots be difficult, the group suggests looking into buying pre-rolled metal tubing for the pot instead.
    a. Finding the tubing may be difficult, but it would eliminate a manufacturing step and would make the process easier.

### 5.3.2 Cost Estimation for Future Production

As mentioned in section 4.3, the estimated cost at scale would be significantly reduced to $99.76 without the solar panel. Once the prototype is finalized and ready for manufacturing, items will be available to purchase at scale which will significantly reduce the price.

# 6 Design Verification and Testing

The following test plans are what would have been conducted during Spring Quarter, had the project taken place in-person. Unfortunately, due to the pandemic, no building phase nor Design Verification or Testing could be done. The goal of these tests is to validate the sub sections and the entire system. The test dates, results, and who performed the tests are all to be determined.

Testing for the ISEC sugar oven will be divided into four stages: detailed design, architectural design, system testing, and acceptance testing. Detailed design testing will be a testing of each individual component. This means a testing of diodes, phase change material, and thermal connectivity from the thermal battery to the pot. These tests will be run in an insulated environment, using thermocouples to measure heat dispersion. The next stage of testing is the architectural design, which is a test of individual systems of the ISEC Sugar Oven. This is a test of the subassemblies within the ISEC. This includes a test of the thermal battery as a system, as well as testing the efficacy of the insulation. The system test will be a test working with all components to see how effectively it cooks a meal. Finally, an acceptance test will be done, bringing the finished product to Ghana, and seeing how it would be accepted within society. All these tests have a specific acceptance criterion, describing how specifications will be met by the tests, as well as how the tests will be run. These are all described in the Design Verification Plan and Report (DVPR) in Appendix I.

## 6.1 Diode Validation Testing

| | |
|---|---|
| **Purpose:** | Test how long it takes for diode chain connected to a voltage source can reach temperature (140°C). Test by having a thermocouple on the body of a diode on the diode chain assuming a uniform temperature along the chain while the voltage source outputs voltage of 100 W solar panel at solar noon (18V). |
| **Scope:** | The goal of this test is to find time for diode to reach 140°C in order to melt the erythritol using a 100 W solar panel. Preparation of diode chain is of primary importance to the procedure. Being able to maintain thermal connection without failure has been an issue with previous ISEC models. |
| **Equipment:** | 1. Square Diodes: BYV10X-600PQ<br>2. Copper Wire<br>3. JB Weld<br>4. Solder<br>5. Voltage source<br>6. Resistive Wire (10 gauge)<br>7. Fiberglass insulation<br>8. Thermocouple<br>9. Thermocouple Data Acquisition System<br>10. Plyers<br>11. Helping Hands |
| **Hazards:** | Electronics, High Heat |

| | |
|---|---|
| **PPE Requirements:** | 1. Safety Goggles<br>2. Heat Resistant Gloves |
| **Facility:** | ISEC LAB in Building 52 |
| **Procedure:** | 1. Bend each diode lead in half 90 degrees away from body of diode using small plyers<br>2. Connect two diodes to helping hands, align bent leads to be parallel and overlapping so that one lead is sitting above another<br>3. Wrap copper wire around the overlapping leads, making sure that it is tight enough so that the leads are fixated with a copper wire coiling around it.<br>4. Solder copper wire and leads together, making sure to use proper soldering technique<br>5. After soldering, apply JB weld to leads as to make a permanent thermal connection.<br>6. Repeat steps to connect 20 diodes in series<br>7. Solder resistive wire to each end of the diode chain<br>8. Connect resistive wire to diode chain, attaching the other end to voltage source<br>9. Heat Tape thermocouple to body of a single diode (assuming uniform distribution of heat)<br>10. Place diode chain in fiberglass insulation<br>11. Set Voltage Source to 18 V<br>12. Track time it takes for thermocouple to reach 140°C<br>13. Map thermocouple on excel to find heating profile of diodes. |
| **Results:** | 1. Pass Criteria:<br>a. Diode reaches 140°C in less than 3 hours<br>2. Fail Criteria<br>a. Diodes do not reach 140°C<br>b. Diodes fail to heat up<br>3. Number of samples to test:<br>a. 3 Diode chains |

## 6.2 Phase Change Material Validation Test (PCM) Validation Test

| | |
|---|---|
| **Purpose:** | Test melting temperature of chosen grade of Erythritol by placing it inside of fully assembled thermal battery with diodes as the heating source. Thermocouple probe with thermocouples at three different levels to be placed inside of thermal battery from hole in top plate. Test time it takes for all erythritol to melt while fully enclosed in fiberglass. |

| | |
|---|---|
| **Scope:** | The goal of this test is multifaceted:<br>1. Find time it takes for this specific grade of erythritol to fully phase change into liquid<br>2. Each thermocouple will be at a different level in the thermal battery; top; middle; and bottom.<br>    a. The purpose of this is to be able to quantify the heating profile, and understanding the amount of time it takes for each level to phase change into a liquid.<br>3. Utilize data collected to report efficacy of use of erythritol in Thermal Battery |
| **Equipment:** | 1. Thermocouples Probe<br>2. Thermocouple Data Acquisition System (DAQ)<br>3. Thermal Battery<br>4. Voltage Source<br>5. Stopwatch<br>6. Gorilla Tape<br>7. Fiberglass insulation |
| **Hazards:** | High Temperatures |
| **PPE Requirements:** | 1. Safety Goggles<br>2. Heat Resistant Gloves |
| **Facility:** | ISEC LAB in Building 52, 111e |
| **Procedure:** | 1. Pour 13.6 kg of crystallized erythritol into thermal battery through hole in top of thermal plate<br>2. Secure thermocouple probe inside of thermal battery through hole in top plate, secure with Gorilla Tape<br>3. Turn on data Thermocouple data acquisition system, making sure to record start time<br>4. Plug in thermal battery to voltage source set to 18V.<br>5. Track thermocouples, mark time it takes for erythritol to reach 140°C<br>6. Once erythritol has fully melted, turn off voltage source, track time it takes for erythritol to solidify.<br>7. Map each thermocouple probe level on Temperature vs. Time plots, mapping important parameters (Time each point takes to boil, peak temperature, time to completely crystallize, time of phase change)<br>8. Use data from each point to map entire heating profile of thermal battery, mapping differences in important parameters (as listed above). |

| | |
|---|---|
| **Results:** | 1. Pass Criteria:<br>    a. Have all PCM melted in no more than 3 hours<br>2. Fail Criteria:<br>    a. PCM doesn't melt at 140°C<br>    b. PCM take more than 3 hours to fully melt<br>3. Number of Samples:<br>    a. 3 trials |

## 6.3 Diode Fatigue Test

| | |
|---|---|
| **Purpose:** | The purpose of this test is to test for failure points of diode chain by having it connected to power source, consistently heating for three 12-hour sessions. This will validate whether there are any short-term failures that can be avoided while running the ISEC, having the diodes ran to spec. |
| **Scope:** | Heating Element Testing |
| **Equipment:** | 1. Diode Chain<br>2. Voltage Source<br>3. Fiberglass insulation<br>4. Thermocouple<br>5. Thermocouple DAQ<br>6. Heat Resistant Tape<br>7. Resistive wire (10 gauge) |
| **Hazards:** | High Temperature |
| **PPE Requirements:** | 1. Safety Goggles<br>2. Heat Resistant Gloves |
| **Facility:** | ISEC room (D-13) in Building 52 |
| **Procedure:** | 1. Tape thermocouple to body of a single diode on the chain<br>2. Plug in thermocouple to DAQ<br>3. Fully Enclose Diode chain in fiberglass insulation<br>4. Connect Diode chain with resistive wire attached to voltage source at 18V<br>5. Have diode chain continuously heating for 12 hours, checking on it periodically (every hour)<br>6. Map thermocouple on excel to find heating profile of thermal battery.<br>7. Repeat Steps 1-6 three times |

| | |
|---|---|
| **Results:** | 1. Pass Criteria:<br>a. Diode chain successfully heats after 36 hours of running consistently<br>2. Fail Criteria:<br>a. Diode chain fails at some point during testing<br>3. Number of Samples:<br>a. Three chains<br>b. Nine 12-hour sessions total |

## 6.4 Thermal Battery Fatigue Sub-System Validation Test

| | |
|---|---|
| **Purpose:** | The purpose of this test is to validate the efficacy of the thermal battery sub-system of the ISEC. This test will be performed by testing time for pot interface of the thermal battery to reach 140°C with a thermocouple. One has reached 140°C, pour room temperature water into pot. Record time to boil water. The entire system will be enclosed in fiberglass and attached to a solar panel as a power source. |
| **Scope:** | The thermal battery is the source of heat for the ISEC and is critical to be able to reach a high enough temperature to boil water. The purpose of this test is to validate the thermal battery as a proper energy source of the ISEC system |
| **Equipment:** | 1. Thermal battery<br>2. Thermocouple (waterproof)<br>3. Thermocouple Data Acquisition System (DAQ)<br>4. Heat Resistant Tape<br>5. Solar Panel<br>6. Fiberglass insulation<br>7. Perlite/Concrete insulation |
| **Hazards:** | High Temperature |
| **PPE Requirements:** | 1. Safety Goggles<br>2. Heat Resistant Gloves |
| **Facility:** | Outside of ISEC lab (Baker Lawn) |

| | |
|---|---|
| **Procedure:** | 1. Tape thermocouple to pot interface of thermal battery<br>2. Connect thermocouple to DAQ<br>3. Connect lead wires from thermal battery to solar panel<br>4. Place thermal battery while fully enclosed in fiberglass insulation, inside of Perlite/Concrete insulation<br>5. Face solar panel facing the sun in order to get proper current to thermal battery.<br>6. Log time it takes to have thermocouple reach 140°C.<br>7. Pour room temperature water into pot interface, filling it 1/2 capacity.<br>8. Log time taken to boil water<br>9. Map thermocouple on excel to find heating profile of thermal battery. |
| **Results:** | 1. Pass Criteria:<br>a. Ability for Pot interface to reach 140°C in ample time ($< 6\ hours$)<br>b. Ability for water to boil<br>2. Fail Criteria:<br>a. Inability for pot interface to reach 140°C<br>b. Inability to boil water<br>3. Number of Samples to Test<br>a. A single thermal battery<br>b. Three repetitions of test |

## 6.5 ISEC System Test

| | |
|---|---|
| **Purpose:** | Working with all components, including pot, insulation, thermal battery to test to see if cooker effectively cooks vegetables and stews commonly eaten in Ghana. Failure test, see if can effectively cook in a reasonable time without failure. |
| **Scope:** | Entire ISEC system |
| **Equipment:** | 1. ISEC<br>a. Thermal Battery<br>b. Fiberglass Insulation<br>c. Pot<br>d. Pot Lid<br>e. Concrete/Perlite Insulation<br>f. Solar Panel<br>2. Vegetable Stew<br>3. Stopwatch<br>4. Thermometer |
| **Hazards:** | High Temperature |
| **PPE Requirements:** | 1. Safety Goggles<br>2. Heat Resistant Gloves |
| **Facility:** | Outside of ISEC lab (Baker Lawn) |
| **Procedure:** | 1. Fully enclose Thermal Battery inside fiberglass and perlite/concrete insulation<br>2. Place perlite/concrete pot lid on top of thermal battery as to store heat in pot interface<br>3. After designated time (predetermined by Thermal Battery Subsystem Test) confirm that pot interface of thermal battery has reached 140°C by removing pot lid and confirming pot interface temperature with a thermometer<br>4. After temperature has been confirmed place pot with stew into pot interface, making sure to place lid on top of the pot.<br>5. Periodically check on stew in 30-minute intervals, being sure to only remove pot lid and fiberglass insulation only momentarily<br>6. Note time taken for stew to fully cook |

| | |
|---|---|
| **Results:** | 1. Pass Criteria:<br>a. Stew cooks with no issues.<br>2. Fail Criteria:<br>a. Stew fails to cook.<br>b. Pot fails to increase in temperature.<br>c. Thermal Battery fails to heat up<br>3. Number of samples to test:<br>a. A single ISEC assembly<br>b. Three repetitions of test |

# 7 Conclusions and Recommendations

The ISEC Sugar Oven has been designed to optimize and simplify usage to be a cheap alternative to biomass cooking in Ghana. Our design minimizes cost, optimizes usability, streamlines manufacturing, as well as reduces risk. Some of the main factors that have been investigated as possible sources of failure have been thermal conductivity of pot and thermal battery and risk of diode failure. Thermal conductivity has been addressed through calculations located in Appendix F. After further analysis and calculations, it has been concluded that to ensure maximum thermal conductivity, a thermally conductive powder will need to be used to interface the pot and thermal battery. Aluminum nitride fits this specification and will be used in the initial prototype of the Sugar Oven. Additionally, making the outer layer of insulation larger in diameter will allow for more fiberglass to be included between the thermal battery and outer insulation. This maintains large transfer ratios, which will in turn maximize thermal conductivity.

## 7.1 Actions to Continue Our Project

Because of the pandemic, our group was unable to confirm the validity of our design with prototype testing this quarter. As it stands, the sugar oven design meets most of the requirements set at the beginning of the year. At the end of the fall quarter, the proposed design developed into a stationary oven, instead of a stove that can be carried. Because of this, the weight requirement for the prototype as a whole was changed to apply just to the removable pot. This requirement then became negligible after the change was made. The one requirement we missed was the cost of the prototype, which initially will be high but would be cheaper if the design is mass manufactured. This estimated cost also was based on if the team had to buy all the materials needed from scratch, when in reality the larger ISEC team has many of the mentioned parts.

Since we were unable to build and test a prototype, should there be any testing failures, possible alternatives to the proposed design could include adjusting the number of diodes used in the heating system or changing the wire used to wrap and connect the diodes in the diode chain. We would also recommend looking into using metal tubing for the pot and thermal battery to eliminate one step in the manufacturing process.

As our senior project comes to an end, we want to recommend what steps could be taken to continue our project and we want to highlight what the larger ISEC team plans to do in the future. With our prototype design ideas, the team can build the proposed prototype and test its subsystems and the final assembly.

## 7.2 ISEC as a Whole

The whole ISEC project will also continue to be actively worked on by a group of volunteers to understand how technology can best be applied to developing countries in an interdisciplinary setting, revisit resistive heating elements, implement the ISEC into other developing countries across the world, and collaborate with non-profits.

# 8 Acknowledgements

The ISEC Team would like to extend our deepest gratitude for our project advisor, Dr. Jim Widmann. Jim provided enormous support throughout the year, not only with engineering guidance, but also with professional and emotional support as well. This project could not have been completed without his care and encouragement. Thank you, Jim!

We would also like to thank the larger ISEC group and the foundation they set for us over the last five years. It was an honor to continue this project and contribute our perspective to the overall ISEC project goal. A special thanks to Owen Staveland for overseeing our project Winter Quarter and answering our myriad of questions, and to our project sponsor and ISEC team lead, Dr. Pete Schwartz.

# 9 Appendix A: References


[1] D. G. Fullerton, N. Bruce and S. B. Gordon, "Indoor air pollution from biomass fuel smoke is a major health concern in the developing world," National Library of Medicine, September 2008. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2568866/. [Accessed June 2020].

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[10] G. Gius, M. Walker, A. Li, N. Adams, R. Van Buskirk and P. Schwartz, "Hot diodes!: Dirt cheap cooking and electricity for the global poor?," *Development Engineering,* vol. 4, no. 100044, 2019.

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# 10 Appendix B: QFD and Decision Matrices

*Table 2. Pugh matrix, showing the evaluation of concepts compared to the Model 3 datum.*

| | DATUM | Alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Criteria | Model 3 | Model 1 | Model 2 | Sugar Stove | Heater Core | Hot Box | Rice Cooker | Multi Hot Spot | Flange ISEC | Threaded ISEC | Sous Vide |
| Cost | 0 | - | 0 | 0 | + | - | 0 | - | - | - | - |
| Manufacturabilty | 0 | - | + | + | + | + | + | 0 | - | - | - |
| Usability | 0 | + | - | + | - | - | + | + | + | + | - |
| Fail Safe | 0 | 0 | + | + | - | + | + | - | + | + | + |
| Efficiency | 0 | - | - | + | - | - | 0 | - | + | 0 | - |
| Weight | 0 | 0 | + | - | + | - | + | 0 | - | - | + |
| Insulated | 0 | 0 | 0 | + | 0 | + | 0 | 0 | 0 | 0 | 0 |
| Food Safe | 0 | 0 | 0 | + | - | + | + | + | + | + | - |
| Sum of positives | 0 | 1 | 3 | 6 | 3 | 4 | 5 | 2 | 4 | 3 | 2 |
| Sum of negatives | 0 | 3 | 2 | 1 | 4 | 4 | 0 | 3 | 3 | 3 | 5 |
| Sum of neutrals | 8 | 4 | 3 | 1 | 1 | 0 | 3 | 3 | 1 | 2 | 1 |
| **Total** | **0** | **-2** | **1** | **5** | **-1** | **0** | **5** | **-1** | **1** | **0** | **-3** |

| | |
|---|---|
| -5 | cost |
| 1 | manufacturability |
| 2 | usability |
| 5 | fail safe |
| -4 | efficiency |
| 0 | weight |
| 2 | insulated |
| 4 | food safe |

Table 2 shows the Pugh matrix made in deciding between the different model ideas. Each model was compared to the Model 3, or current design of the ISEC with the design requirements given. If the alternative for certain criteria was predicted to be better than the current condition, it was given a positive score; if it was predicted to be worse, it was given a negative score; and if it was predicted to be the same as the Model 3, it was given a neutral (0) score. Positive scores are highlighted in red, negative scores are highlighted in green, and neutral scores were left white or grey.

*Table 3. Quality Function Deployment (QFD).*

| People who cook in Ghana | | Engineering Requirements | | | | | | | | | | | | | Bench marks | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Weighting (1 to 5) | 100 W Solar Panel | Weight < 30 lbs | Production cost < $100 | <10% heat loss | Food safe/no contamination | Ghanain Aluminum pots | Resources found in Ghana | Diode heating element | Manufactured in Ghana | Reproducable | Electrical system isolated from all liquids | Ability to measure temperature | Current biomass cooking | Solar slow cookers |
| Customer Requirements | Low cost | 5 | ● | Δ | ● | | | ○ | ● | ○ | ● | Δ | Δ | ○ | 5 | 3 |
| | Zero biomass emissions | 5 | ● | | Δ | | | | ● | ● | | | | | 1 | 5 |
| | Above ground | 4 | Δ | | Δ | ○ | ● | | Δ | | | Δ | | | 5 | 4 |
| | Easy to clean | 3 | | ○ | Δ | ○ | Δ | ○ | Δ | ○ | | Δ | ● | Δ | 5 | 3 |
| | Phone charging capabilities | 3 | | Δ | ○ | | Δ | | ● | ● | ● | Δ | | | 1 | 1 |
| | Solar electric | 5 | ● | | ● | | | | ● | Δ | Δ | | | | 1 | 5 |
| | Cooking abilities | - | | | | | | | | | | | | | | |
| | Slow cook | 5 | Δ | | | ○ | Δ | Δ | ● | ● | | | ● | Δ | 5 | 5 |
| | Simmer | 5 | Δ | | | ○ | Δ | Δ | ● | ● | | | ● | Δ | 5 | 1 |
| | Sautee | 5 | Δ | | | ○ | Δ | Δ | ● | ● | | | ● | Δ | 5 | 1 |
| | Boil | 5 | Δ | | | ○ | Δ | Δ | ● | ● | | | ● | Δ | 5 | 1 |
| | Reliable | 4 | ○ | | | ○ | ○ | | ● | ● | | ○ | ● | ○ | 5 | 4 |
| | Intuitive technology | 2 | Δ | Δ | Δ | | | | ● | ○ | ○ | Δ | Δ | ● | 5 | 3 |
| | Units | | W | lbs | $ | % | | | | | | | | | | |
| | Targets | | 100 | <30 | <100 | <10 | | | | | | | | | | |
| | Current biomass cooking | | 1 | 5 | 5 | 2 | 4 | 5 | 5 | 1 | 5 | 3 | 3 | 1 | | |
| | Solar slow cookers | | 5 | 3 | 2 | 3 | 4 | 3 | 3 | 4 | 3 | 4 | 2 | 3 | | |
| | Importance Scoring | | 173 | 19 | 113 | 93 | 74 | 44 | 439 | 332 | 83 | 29 | 250 | 68 | | |
| | Importance Rating (%) | | 39 | 4 | 26 | 21 | 17 | 10 | 100 | 76 | 19 | 7 | 57 | 15 | | |

● = 9 Strong Correlation

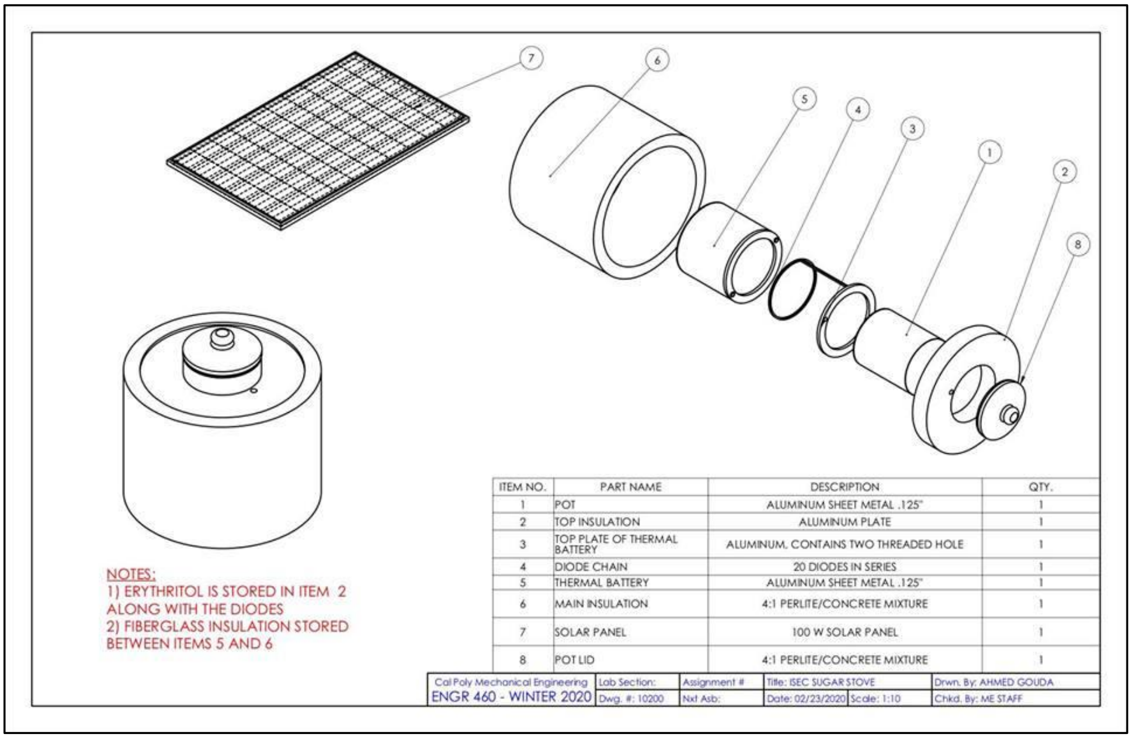
○ = 3 Medium Correlation

Δ = 1 Small Correlation

Blank No Correlation

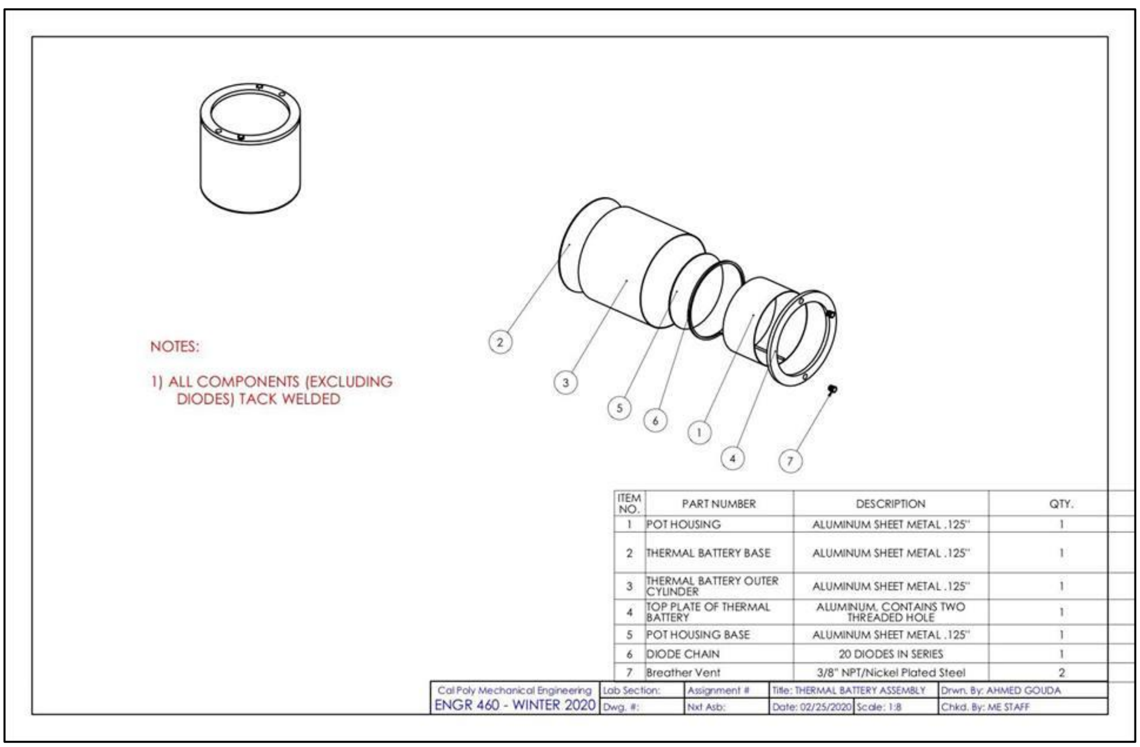
Table 3 shows the Quality Function Deployment, or the QFD. This shows the correlation strength between the end-user and the engineering requirements given.

# 11 Appendix C: Final Drawings




| ITEM NO. | PART NAME | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | POT | ALUMINUM SHEET METAL .125" | 1 |
| 2 | TOP INSULATION | ALUMINUM PLATE | 1 |
| 3 | TOP PLATE OF THERMAL BATTERY | ALUMINUM, CONTAINS TWO THREADED HOLE | 1 |
| 4 | DIODE CHAIN | 20 DIODES IN SERIES | 1 |
| 5 | THERMAL BATTERY | ALUMINUM SHEET METAL .125" | 1 |
| 6 | MAIN INSULATION | 4:1 PERLITE/CONCRETE MIXTURE | 1 |
| 7 | SOLAR PANEL | 100 W SOLAR PANEL | 1 |
| 8 | POT LID | 4:1 PERLITE/CONCRETE MIXTURE | 1 |

*Figure 11. Bill of Materials (BOM).*




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | POT HOUSING | ALUMINUM SHEET METAL .125" | 1 |
| 2 | THERMAL BATTERY BASE | ALUMINUM SHEET METAL .125" | 1 |
| 3 | THERMAL BATTERY OUTER CYLINDER | ALUMINUM SHEET METAL .125" | 1 |
| 4 | TOP PLATE OF THERMAL BATTERY | ALUMINUM, CONTAINS TWO THREADED HOLE | 1 |
| 5 | POT HOUSING BASE | ALUMINUM SHEET METAL .125" | 1 |
| 6 | DIODE CHAIN | 20 DIODES IN SERIES | 1 |
| 7 | Breather Vent | 3/8" NPT/Nickel Plated Steel | 2 |

*Figure 12. Thermal Battery.*

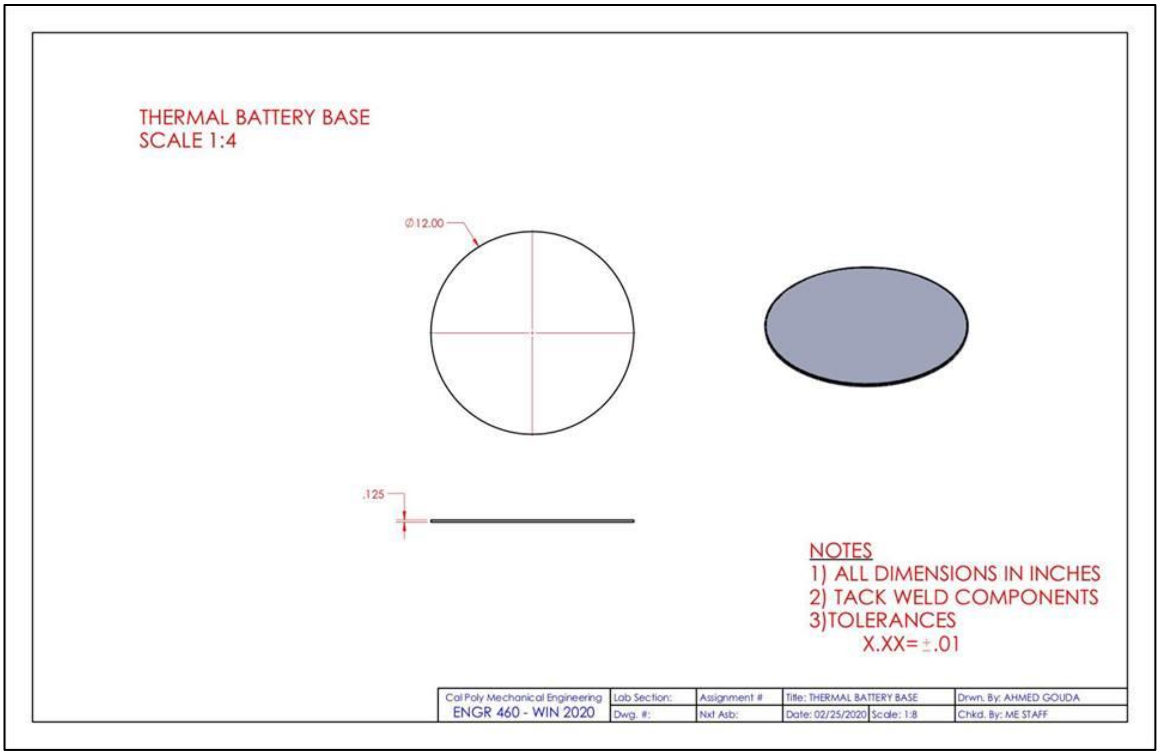



*Figure 13. Thermal Battery Base.*

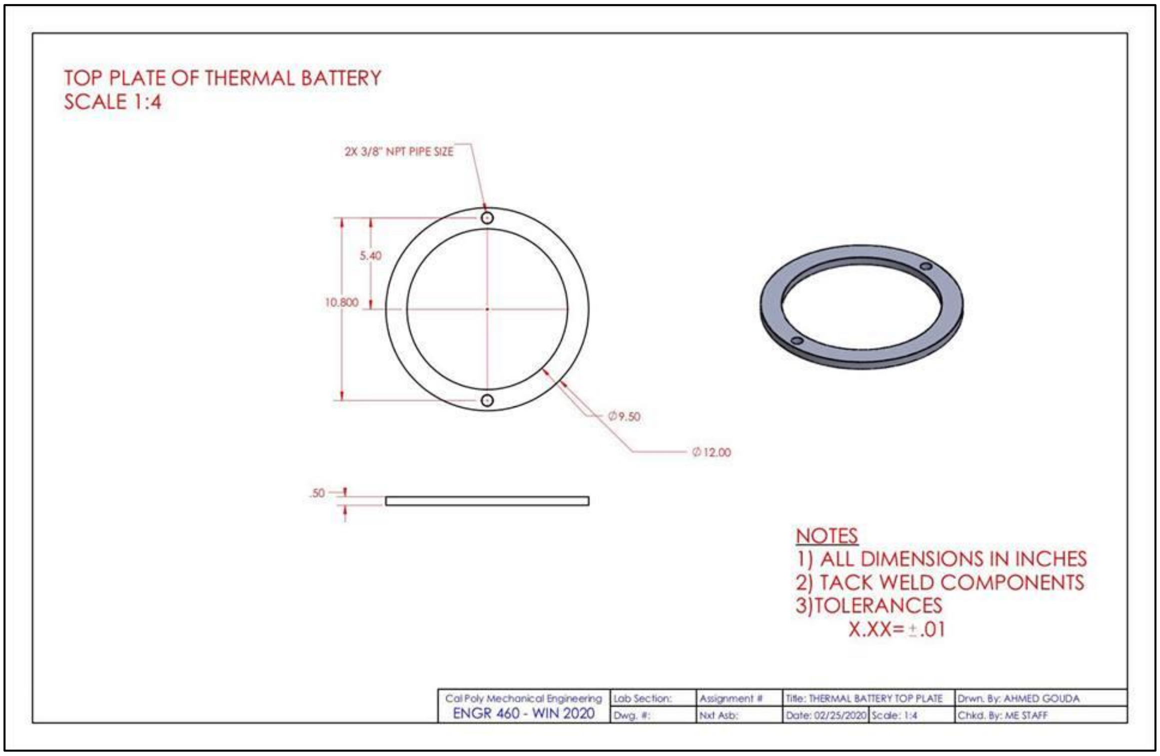



*Figure 14. Top Plate of Thermal Battery.*

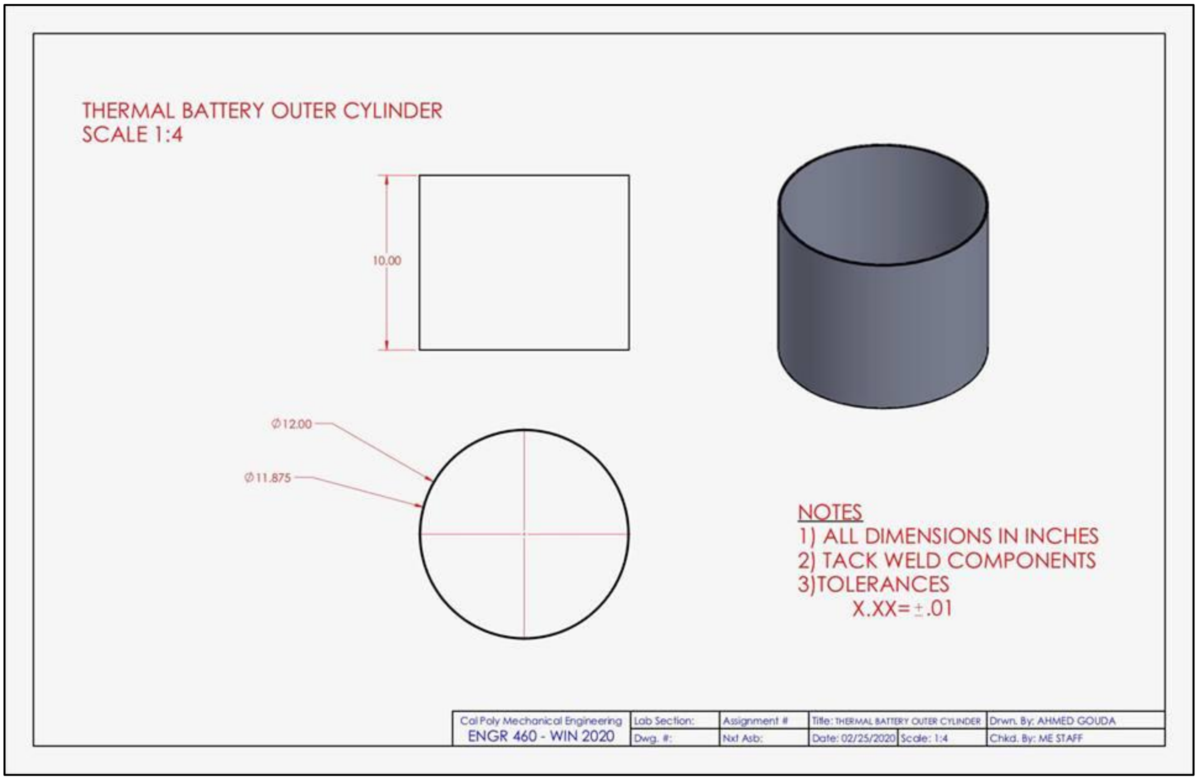



*Figure 15. Thermal Battery Outer Cylinder.*

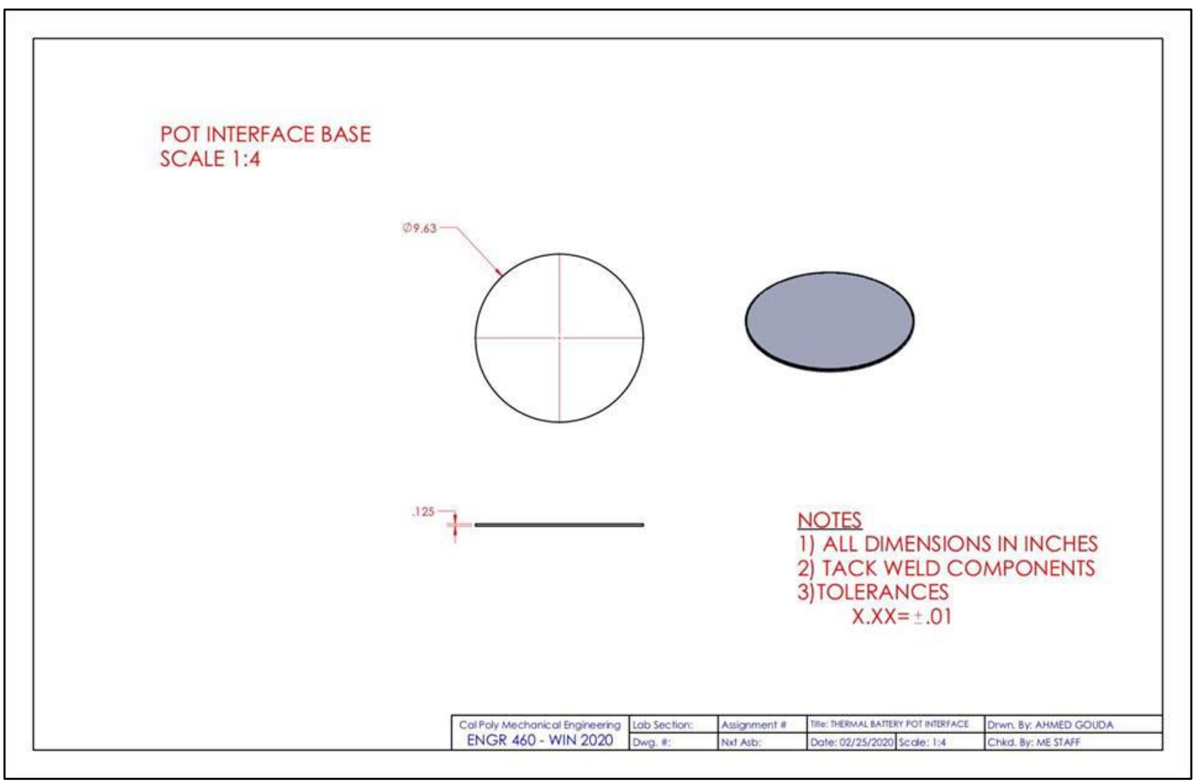



*Figure 16. Pot Interface Base, Scale 1:4.*

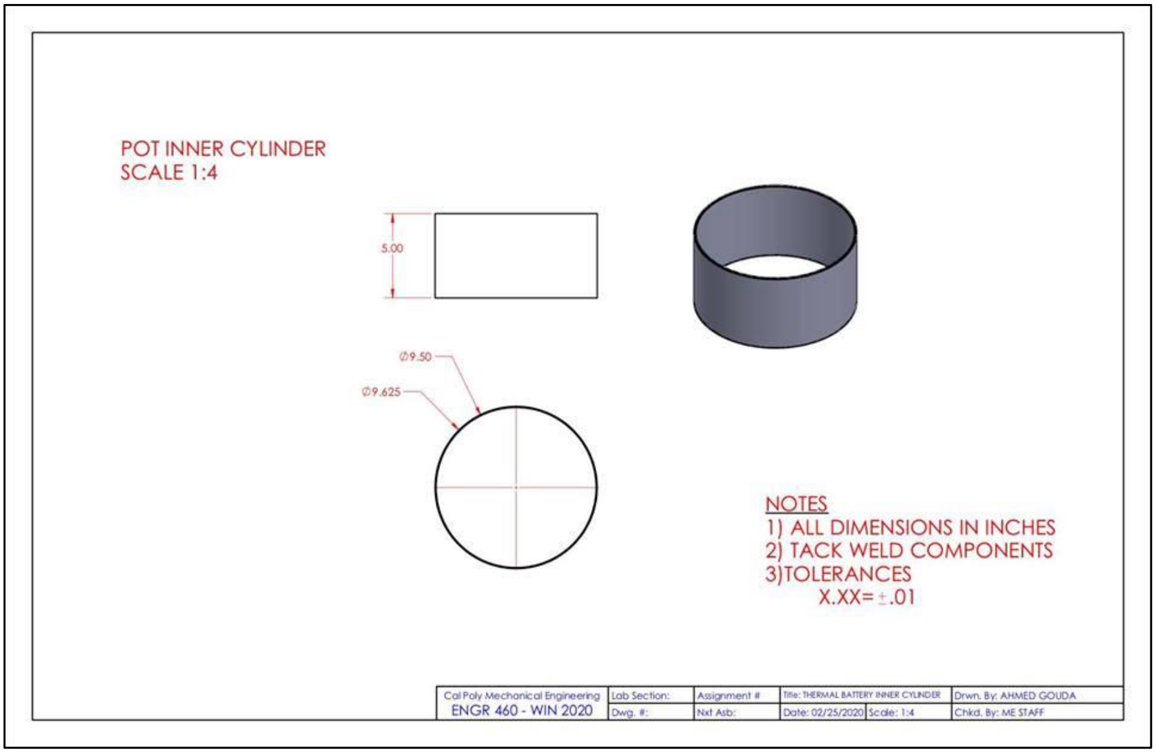



*Figure 17. Pot Interface Cylinder.*

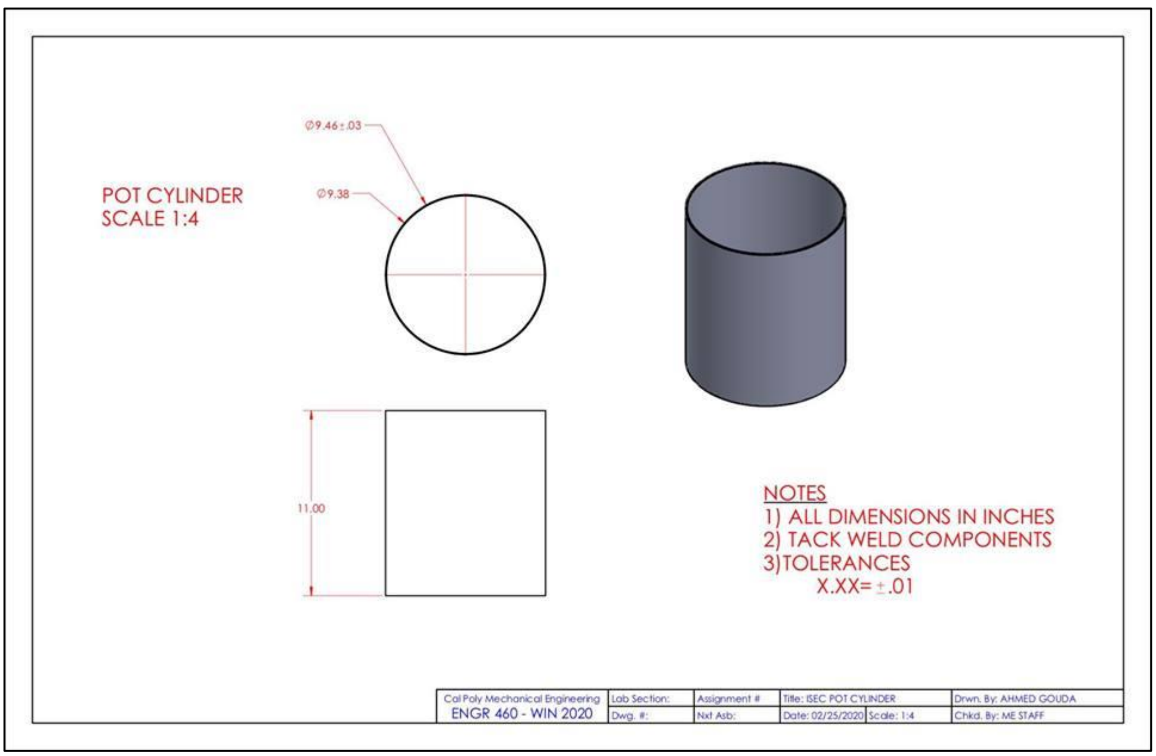



*Figure 18. Pot Cylinder.*

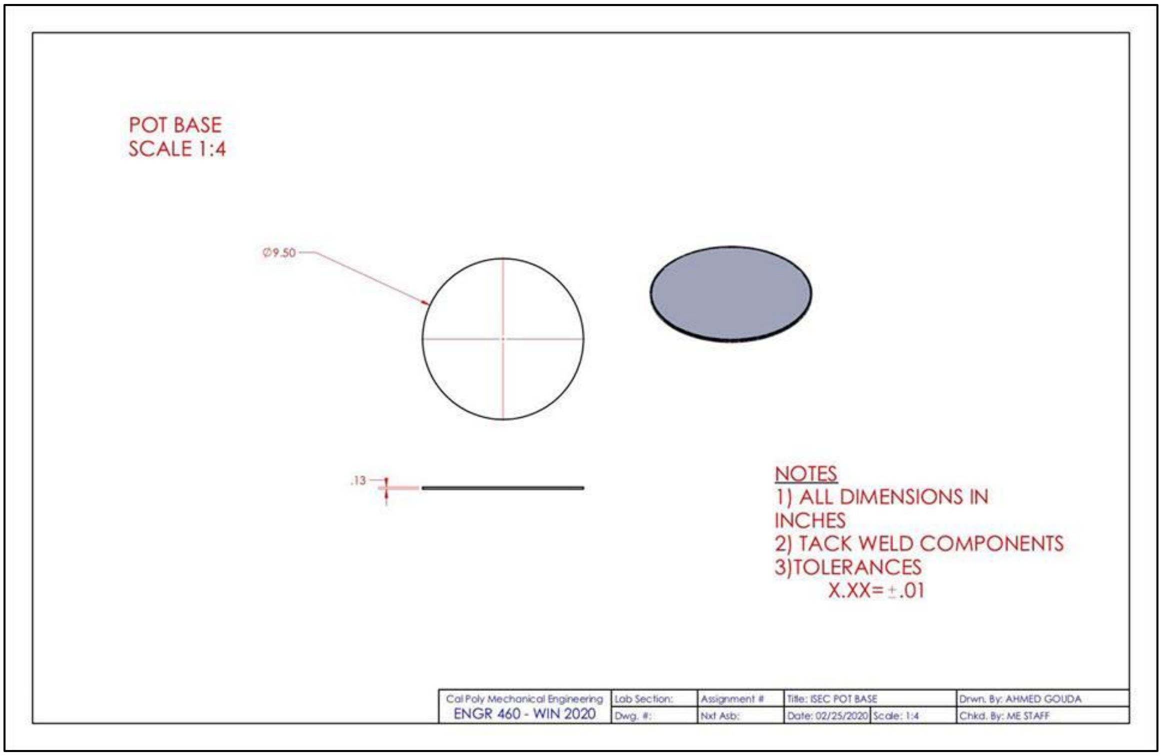



*Figure 19. Pot Base.*

Figures 11 through 19 show the full assembly and its subcomponents of the Sugar Oven.

# 12 Appendix D: List of Vendors, Contact Information, and Pricing

Tables 4 and 5 highlight the raw materials we are planning on using in our model. The cost analysis has been updated since Winter Quarter based on suppliers and calculated quantity amounts, but the estimated cost at scale remains the same.

*Table 4. Bill of Materials, List Form.*

| Vendor | Item | Part Number | Qty. | Cost/Quantity | Total Cost |
|---|---|---|---|---|---|
| Amazon | **Erythritol Sweetener Granular (2.5 lb. / 40 oz)** | none | 1 | $ 14.99 | $ 14.99 |
| Amazon | JB Weld 8281 (10 oz) | none | 1 | $ 14.79 | $ 14.79 |
| DigiKey | Diode Standard 600V 10A Through Hole | BYV10X-600PQ | 16 | $ 0.41 | $ 6.48 |
| Grainger | Loose Absorbent, Universal, Perlite, 8 gal. | PLP900-1 | 1 | $ 19.90 | $ 19.90 |
| Grape Solar | High Efficiency Polycrystalline Photovoltaic Module | GS-STAR-100W | 1 | $ 100.00 | $ 100.00 |
| Lowes | QUIKRETE 90-lb High Strength Concrete Mix | none | 1 | $ 4.10 | $ 4.10 |
| McMaster-Carr | Multipurpose 6061 Aluminum Sheet (48" x 48“) | 89015K126 | 1 | $ 88.33 | $ 88.33 |
| McMaster-Carr | Multipurpose 6061 Aluminum, 10" Diameter | 1610t68 | 1 | $ 61.12 | $ 61.12 |
| McMaster-Carr | Breather Vent | 9833k23 | 1 | $ 2.44 | $ 2.44 |
| McMaster-Carr | Push-In Connector Set, 2 Poles, 15 Amps | 9193t12 | 1 | $ 17.27 | $ 17.27 |
| McMaster-Carr | Fiberglass Insulation | 9346k38 | 2 | $ 40.08 | $ 80.16 |
| McMaster-Carr | Copper Wire, 1/4 lb. Spool, 0.020" Diameter | 8873K22 | 1 | $ 6.87 | $ 6.87 |
| | | **Total** | | $ 370.30 | $ 416.45 |

*Table 5. Cost Analysis from Winter Quarter.*

| Item | Cost (in USD) | Estimated Cost at Scale |
|---|---|---|
| Diode Chain | 11.40 | 4.50 |
| Aluminum Sheet Metal | TBD, ~60.00 | TBD, ~30.00 |
| Perlite | 16.00 | 4.00 |
| Concrete | 4.10 | 2.00 |
| Erythritol | TBD, ~1 kg. for 10.00 | TBD, ~1 kg for 4.48 |
| JB Weld | 5.00 | 2.00 |
| Fiberglass Insulation | 15.00 | 2.50 |
| Breather Plug | 2.44 | 1.00 |
| **SUBTOTAL** | **233.94** | **99.76** |
| Solar Panel | 80.00 | 60.00 |
| **TOTAL** | **310.94** | **159.76** |

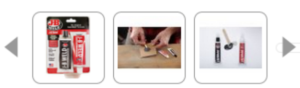
| Assembly Level | Part/Drawing Number | Description Lvl0 | Lvl1 | Lvl2 | Lvl3 | Lvl4 | Vendor | Qty | Cost | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | Final Assembly | | | | | | | | |
| 1 | | | ISEC | | | | | | | |
| 2 | | | | Pot | | | | | | |
| 3 | | | | | Aluminum sheet | | McMaster-Carr | 1 | $ 88.33 | $ 88.33 |
| 3 | | | | | Aluminum disc | | McMaster-Carr | 1 | $ 61.12 | $ 61.12 |
| 2 | | | | Battery | | | | | | |
| 3 | | | | | Battery top | | | | | |
| 4 | | | | | | Aluminum disc | | | | |
| 4 | | | | | | Breather vent | McMaster-Carr | 1 | $ 2.44 | $ 2.44 |
| 3 | | | | | Anchor | | | | | |
| 4 | | | | | | Aluminum sheet | | | | |
| 3 | | | | | Case | | | | | |
| 4 | | | | | | Aluminum sheet | | | | |
| 3 | | | | | Electrical system | | | | | |
| 4 | | | | | | Diodes | DigiKey | 16 | $ 0.41 | $ 6.48 |
| 4 | | | | | | Copper wire | McMaster-Carr | 1 | $ 6.87 | $ 6.87 |
| 4 | | | | | | Electrical connector | McMaster-Carr | 1 | $ 17.27 | $ 17.27 |
| 3 | | | | | Erythritol | | Amazon | 1 | $ 14.99 | $ 14.99 |
| 3 | | | | | JB Weld | | Amazon | 1 | $ 14.79 | $ 14.79 |
| 2 | | | | Housing | | | | | | |
| 3 | | | | | Housing wall | | | | | |
| 4 | | | | | | Concrete | Lowes | 1 | $ 4.10 | $ 4.10 |
| 4 | | | | | | Perlite | Grainger | 1 | $ 19.90 | $ 19.90 |
| 4 | | | | | | Fiberglass | McMaster-Carr | 2 | $ 40.08 | $ 80.16 |
| 3 | | | | | Housing roof | | | | | |
| 4 | | | | | | Concrete | | | | |
| 4 | | | | | | Perlite | | | | |
| 3 | | | | | Housing lid | | | | | |
| 4 | | | | | | Concrete | | | | |
| 4 | | | | | | Perlite | | | | |
| 1 | | | Solar Panel | | | | GrapeSolar | 1 | $ 100.00 | $ 100.00 |
| | | | | | | | Total Parts | 28 | $ 370.30 | $ 416.45 |

*Figure 20. Indented Bill of Materials.*

Figure 19 displays the indented bill of materials.

# 13 Appendix E: Vendor Supplied Content Specifications and Data Sheets

The following sheets outline the vendor supplied content specifications for all the components. The sheets are in the order that they are listed in the Bill of Materials table, except for the QUIKRETE 90-lb High Strength Concrete Mix Specification Sheet.

| | |
|---|---|
| STRENGTH | 5020 PSI |
| SET TIME | 4-6 Hours |
| CURE TIME | 15-24 Hours |
| CURE COLOR | Dark Gray |

***J-B WELD™ PROFESSIONAL SIZE 10 OZ***

SKU: 8281

*$ 19.99*

**ADD TO CART**

J-B Weld™ is The Original Cold Weld two-part epoxy system that provides strong, lasting repairs to metal and multiple surfaces. Mixed at a ratio of 1:1, it forms a permanent bond and can be shaped, tapped, filed, sanded and drilled after curing. At room temperature, J-B Weld™ sets in 4-6 hours to a dark grey color. A full cure is reached in 15-24 hours. J-B Weld™ has a tensile strength of 5020 PSI and sets to a hard bond overnight. It can withstand temperatures up to 550°F when fully cured.

GREAT FOR

- Household Repairs
- Automotive
- Plumbing
- Marine
- Crafts & More

USE ON

- Automotive
- Brick
- Concrete
- J-B Weld
- Metal
- And More

***Get The Safety Data Sheet***

***For California residents only, check here for warning***

QUIKRETE 90-lb High Strength Concrete Mix Specification Sheet

**Specifications**

| | |
|---|---|
| **Series Name** | N/A |
| **Weight (lbs.)** | 90 |
| **Compression Strength (PSI)** | 4000 |
| **Color/Finish Family** | Gray |
| **Warranty** | 1-year limited |
| **Dry to Walk** | 24 hours |
| **Type** | High strength |

| | |
|---|---|
| **CA Residents: Prop 65 Warning(s)** | ⚠ **Prop 65 WARNING(S)** |
| **Curing Time (Days)** | 28 |
| **Working Time in Minutes** | 60 |
| **Set Time (Minutes)** | 300 |
| **UNSPSC** | 30111500 |
| **Drive on Time (Hours)** | 168 |

WeEn
WeEn Semiconductors

# BYV10X-600P

## Ultrafast power diode

26 September 2018 Product data sheet

## 1. General description

Ultrafast power diode in a SOD113 (2-lead TO-220F) plastic package.

## 2. Features and benefits

- Fast switching
- Isolated plastic package
- Low leakage current
- Low forward voltage drop
- Low thermal resistance
- Soft recovery characteristic

## 3. Applications

- High frequency switched-mode power supplies
- Discontinuous Current Mode (DCM) Power Factor Correction (PFC)

## 4. Quick reference data

**Table 1. Quick reference data**

| Symbol | Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|
| $V_R$ | reverse voltage | DC | - | - | 600 | V |
| $I_{F(AV)}$ | average forward current | $\delta = 0.5$ ; $T_h \leq 71$ °C; square-wave pulse; Fig. 1; Fig. 2; Fig. 3 | - | - | 10 | A |
| $I_{FSM}$ | non-repetitive peak forward current | $t_p = 10$ ms; $T_{j(init)} = 25$ °C; sine-wave pulse; Fig. 4 | - | - | 80 | A |
| | | $t_p = 8.3$ ms; $T_{j(init)} = 25$ °C; sine-wave pulse | - | - | 88 | A |
| **Static characteristics** | | | | | | |
| $V_F$ | forward voltage | $I_F = 10$ A; $T_j = 25$ °C; Fig. 6 | - | 1.5 | 2 | V |
| | | $I_F = 10$ A; $T_j = 150$ °C; Fig. 6 | - | - | 1.6 | V |
| **Dynamic characteristics** | | | | | | |
| $t_{rr}$ | reverse recovery time | $I_F = 1$ A; $V_R = 30$ V; $dI_F/dt = 50$ A/µs; $T_j = 25$ °C; Fig. 7 | - | 35 | 50 | ns |

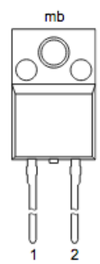
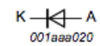
WeEn Semiconductors

**BYV10X-600P**

**Ultrafast power diode**

## 5. Pinning information

**Table 2. Pinning information**

| Pin | Symbol | Description | Simplified outline | Graphic symbol |
|---|---|---|---|---|
| 1 | K | cathode |   TO-220F (SOD113) |   |
| 2 | A | anode | | |
| mb | n.c. | mounting base; isolated | | |

## 6. Ordering information

**Table 3. Ordering information**

| Type number | Package | | |
|---|---|---|---|
| | Name | Description | Version |
| BYV10X-600P | TO-220F | plastic single-ended package; isolated heatsink mounted; 1 mounting hole; 2-lead TO-220 "full pack" | SOD113 |

**WeEn Semiconductors** **BYV10X-600P**

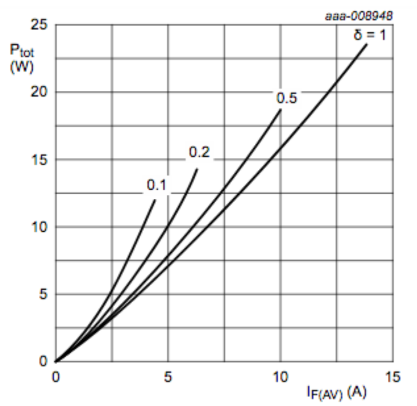
**Ultrafast power diode**

## 7. Limiting values

**Table 4. Limiting values**

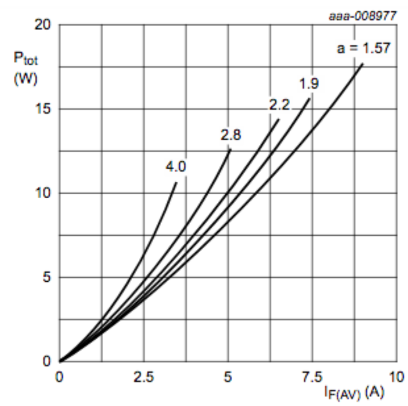
*In accordance with the Absolute Maximum Rating System (IEC 60134).*

| Symbol | Parameter | Conditions | | Min | Max | Unit |
|---|---|---|---|---|---|---|
| $V_{RRM}$ | repetitive peak reverse voltage | | | - | 600 | V |
| $V_{RWM}$ | crest working reverse voltage | | | - | 600 | V |
| $V_R$ | reverse voltage | DC | | - | 600 | V |
| $I_{F(AV)}$ | average forward current | δ = 0.5 ; $T_h \leq$ 71 °C; square-wave pulse; Fig. 1; Fig. 2; Fig. 3 | | - | 10 | A |
| $I_{FRM}$ | repetitive peak forward current | δ = 0.5 ; $t_p$ = 25 µs; $T_h \leq$ 71 °C; square-wave pulse | | - | 20 | A |
| $I_{FSM}$ | non-repetitive peak forward current | $t_p$ = 10 ms; $T_{j(init)}$ = 25 °C; sine-wave pulse; Fig. 4 | | - | 80 | A |
| | | $t_p$ = 8.3 ms; $T_{j(init)}$ = 25 °C; sine-wave pulse | | - | 88 | A |
| $T_{stg}$ | storage temperature | | | -65 | 175 | °C |
| $T_j$ | junction temperature | | | - | 175 | °C |




$I_{F(AV)} = I_{F(RMS)} \times \sqrt{\delta}$
$V_o$ = 1.268 V; $R_s$ = 0.031 Ω

**Fig. 1. Forward power dissipation as a function of average forward current; square waveform; maximum values**




a = form factor = $I_{F(RMS)}$ / $I_{F(AV)}$
$V_o$ = 1.268 V; $R_s$ = 0.031 Ω

**Fig. 2. Forward power dissipation as a function of average forward current; sinusoidal waveform; maximum values**

WeEn Semiconductors

**BYV10X-600P**

**Ultrafast power diode**

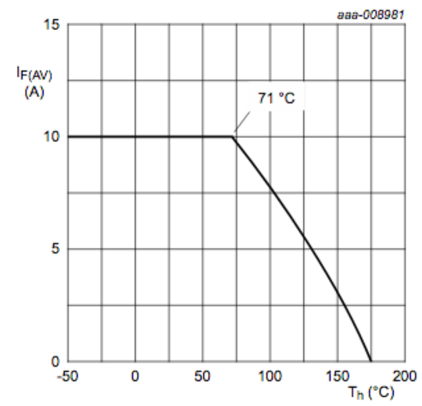



**Fig. 3. Forward current as a function of heatsink temperature; maximum values**

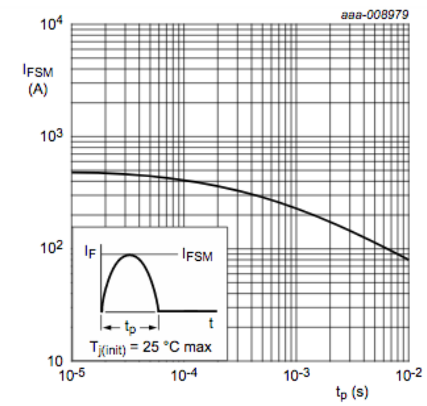



**Fig. 4. Non-repetitive peak forward current as a function of pulse width; sinusoidal waveform; maximum values**

WeEn Semiconductors

**BYV10X-600P**

**Ultrafast power diode**

## 8. Thermal characteristics

**Table 5. Thermal characteristics**

| Symbol | Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|
| $R_{th(j-h)}$ | thermal resistance from junction to heatsink | without heatsink compound | - | - | 7.2 | K/W |
| | | with heatsink compound; Fig. 5 | - | - | 5.5 | K/W |
| $R_{th(j-a)}$ | thermal resistance from junction to ambient free air | in free air | - | 55 | - | K/W |

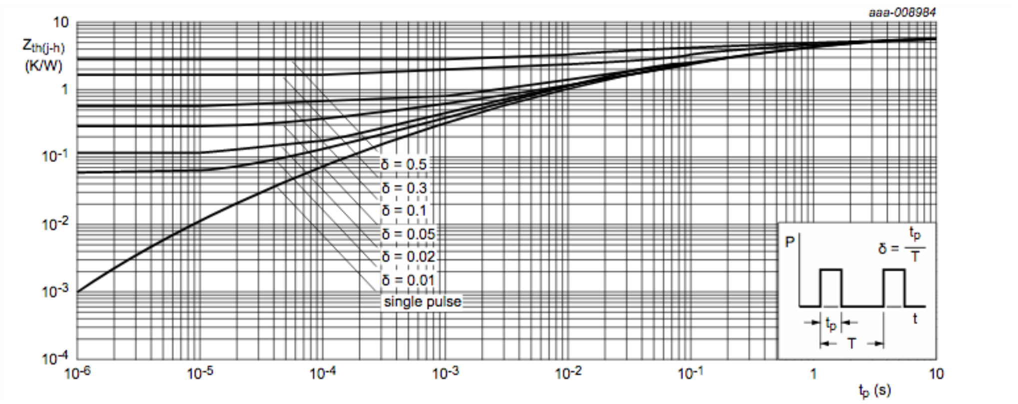



**Fig. 5. Transient thermal impedance from junction to heatsink as a function of pulse duration**

## 9. Isolation characteristics

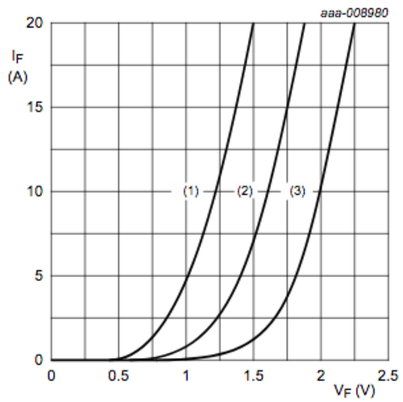
**Table 6. Isolation characteristics**

| Symbol | Parameter | Conditions | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|
| $V_{isol(RMS)}$ | RMS isolation voltage | 50 Hz ≤ f ≤ 60 Hz; RH ≤ 65 %; from all pins to external heatsink; sinusoidal waveform; clean and dust free | - | - | 2500 | V |
| $C_{isol}$ | isolation capacitance | from cathode to external heatsink | - | 10 | - | pF |

## 10. Characteristics

**Table 7. Characteristics**

| Symbol | Parameter | Conditions | | Min | Typ | Max | Unit |
|---|---|---|---|---|---|---|---|
| **Static characteristics** | | | | | | | |
| $V_F$ | forward voltage | $I_F$ = 10 A; $T_j$ = 25 °C; Fig. 6 | | - | 1.5 | 2 | V |
| | | $I_F$ = 10 A; $T_j$ = 150 °C; Fig. 6 | | - | - | 1.6 | V |
| $I_R$ | reverse current | $V_R$ = 600 V; $T_j$ = 25 °C | | - | - | 10 | µA |
| | | $V_R$ = 500 V; $T_j$ = 150 °C | | - | - | 250 | µA |
| **Dynamic characteristics** | | | | | | | |
| $t_{rr}$ | reverse recovery time | $I_F$ = 1 A; $V_R$ = 30 V; $dI_F/dt$ = 50 A/µs; $T_j$ = 25 °C; Fig. 7 | | - | 35 | 50 | ns |
| | | $I_F$ = 1 A; $V_R$ = 30 V; $dI_F/dt$ = 100 A/µs; $T_j$ = 25 °C; Fig. 7 | | - | 20 | - | ns |
| | | $I_F$ = 10 A; $V_R$ = 200 V; $dI_F/dt$ = 200 A/µs; $T_j$ = 25 °C; Fig. 7 | | - | 40 | - | ns |




$V_o$ = 1.268 V; $R_s$ = 0.031 Ω
(1) $T_j$ = 150 °C; typical values
(2) $T_j$ = 150 °C; maximum values
(3) $T_j$ = 25 °C; maximum values

**Fig. 6. Forward current as a function of forward voltage**

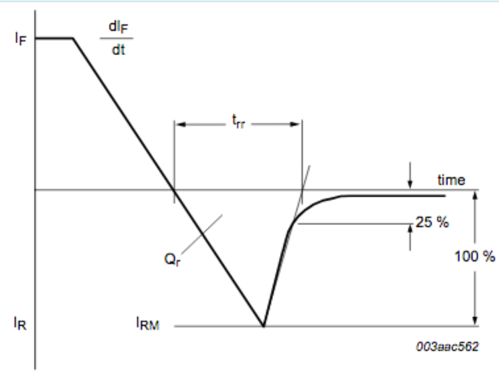
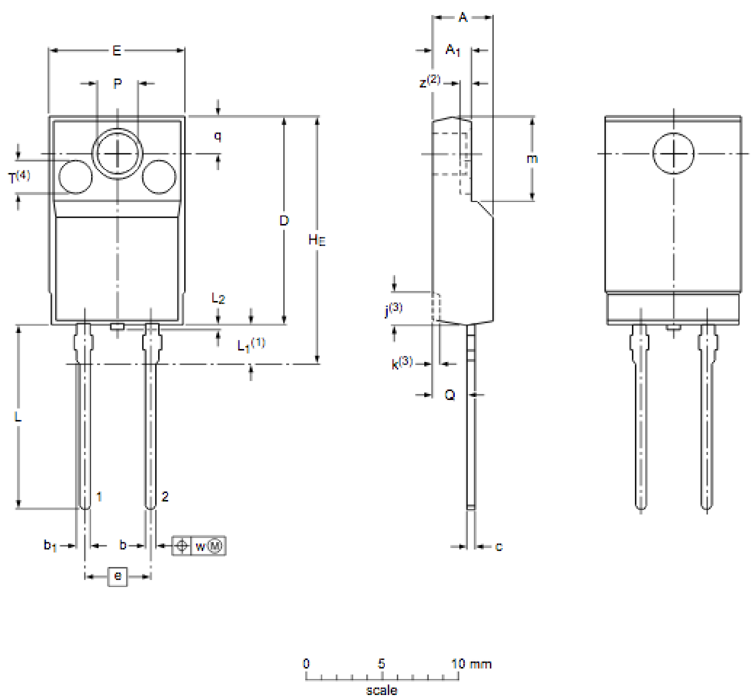



**Fig. 7. Reverse recovery definitions; ramp recovery**

## 11. Package outline

Plastic single-ended package; isolated heatsink mounted;
1 mounting hole; 2-lead TO-220 'full pack' SOD113




Dimensions (mm are the original dimensions)

| Unit | | A | $A_1$ | b | $b_1$ | c | D | E | e | $H_E$ max | j(3) | k(3) | L | $L_1$(1) | $L_2$ max | m | P | Q | q | T(4) | w | z(2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | max | 4.6 | 2.9 | 0.9 | 1.1 | 0.7 | 15.8 | 10.3 | | | 2.7 | 0.6 | 14.4 | 3.3 | | 6.5 | 3.2 | 2.6 | | | | |
| | nom | | | | | | | | 5.08 | 19.0 | | | | | 0.5 | | | | 2.6 | 2.55 | 0.4 | 0.8 |
| | min | 4.0 | 2.5 | 0.7 | 0.9 | 0.4 | 15.2 | 9.7 | | | 1.7 | 0.4 | 13.5 | 2.8 | | 6.3 | 3.0 | 2.3 | | | | |

Notes
1. Terminals are uncontrolled within zone L1.
2. z is depth of T.
3. Dot lines area designs may vary.
4. Eject pin mark is for reference only.

sod113_po

| Outline version | References IEC | JEDEC | JEITA | | European projection | Issue date |
|---|---|---|---|---|---|---|
| SOD113 | | 2-lead TO-220F | | | | ~~07-06-08~~ 15-08-28 |

**Fig. 8. Package outline TO-220F (SOD113)**

# PIG® Sheen Clean® Loose Absorbent

## #PLP900-1 - Absorbs Oils, Coolants, Solvents & Water • 1 - 10 lb. Bag


Gets into small cracks and crevices on the floor to remove the slippery sheen residue that's left from spill cleanup.

- Helps reduce slips and falls by quickly absorbing spills and removing the liquid residue that can leave floors slick and dangerous
- Fine, granular absorbent gets into cracks and crevices to help remove trapped liquids; a good final step for spill cleanup
- Quickly absorbs oils, coolants, solvents, water, paint or viscous liquids for easier cleanup
- Specially formulated to minimize dust
- Highly absorbent so you use less and save on disposal
- Lightweight and easy to use
- Resealable bag keeps moisture in to help prevent drying, so product performs consistently from start to finish
- Gusseted sides make bag easier to store and pour

Always in stock. Ships within 24 hours.

New Pig

By Phone: 1-855-493-HOGS | Online: newpig.com | Email: hothogs@newpig.com

One Pork Avenue • Tipton PA 16684-0304

## PLP900-1 Specifications

| | |
|---|---|
| **Color:** | White |
| **Fluids Absorbed:** | Oils, Coolants, Solvents & Water |
| **Absorbency:** | Up to 8 gal. per bag |
| **Volume:** | 10 lb. Bag |
| **Sold as:** | 1 bag |
| **Weight:** | 11 lbs. |
| **National Stock Number (NSN):** | 4235-01-528-0362 |
| **# per Pallet:** | 50 |
| **Composition:** | Perlite |
| **UNSPSC:** | 47131902 |

## PLP900-1 Metric Equivalent

| | |
|---|---|
| **Absorbency:** | Up to 30.3 L per bag |
| **Weight:** | 5 kg |

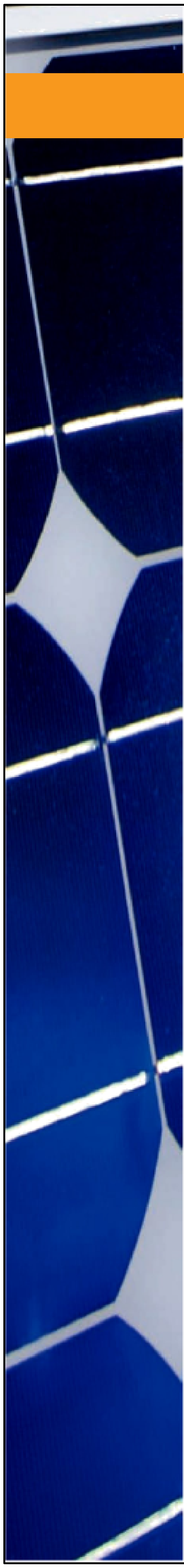
## Technical Information

**Warnings & Restrictions:**
Hydrofluoric Acid Notice
Do not use with hydrofluoric acid.

**Regulations and Compliance:**
29 CFR 1910.22(a) - All places of employment "shall be kept clean and dry and in a sanitary condition" and floors shall be kept clean and dry.

**Technical Documents:**
(Available at newpig.com)
Product Data Sheet (PDS)
Safety Data Sheet (SDS)

pig
New Pig
By Phone: 1-855-493-HOGS
Online: newpig.com
Email: hothogs@newpig.com
One Pork Avenue • Tipton PA 16684-0304



**MODEL: GS-STAR-100W**

Grape Solar®
Clean Power. Today.

## High Efficiency Polycrystalline Photovoltaic Module

**Overview**

- High efficiency solar cells with quality silicon material for high module conversion efficiency and long term output stability and reliability.
- Rigorous quality control to meet the highest international standards.
- High transmittance, low iron tempered glass with enhanced stiffness and impact resistance.
- Unique frame design with strong mechanical strength for up to 50 lbs/ft$^2$ wind load and snow load withstanding and easy installation.
- Advanced encapsulation material with multilayer sheet lamination to provide long-life and enhanced cell performance.
- Outstanding electrical performance under high temperature and weak light environments.
- Built in bypass diodes.

**Applications**

- Emergency Backup, RVs, Pumps, Gates, Electric Fences, Lighting, 12 Volt Battery Charging and much more.

**Warranty**

- 5 year limited product warranty on materials and workmanship.
- 25 year warranty on >80% power output and 10 year warranty on >90% power output.
- Refer to warranty document for detailed warranty information.

**Mechanical Specifications** (note: module dimensions may have +/- 1% variance)

| Characteristic | Details |
|---|---|
| Cell Size | 156mm x 104mm (6.14" x 4.40") |
| Module Dimension (L x W x T) | 1020mm x 670mm x 35mm (40.16" x 26.37" x 1.38") |
| No. of Cells | 36 |
| Weight | 8.2 kg (18.11 lbs) |
| Cable Length | 900mm for positive (+) and negative (-) |
| Type of Connector | MC-IV comparable |
| Junction Box | IP65 Rated |
| No. of Holes in Frame | 4 installation holes |

Rev.02• 1611

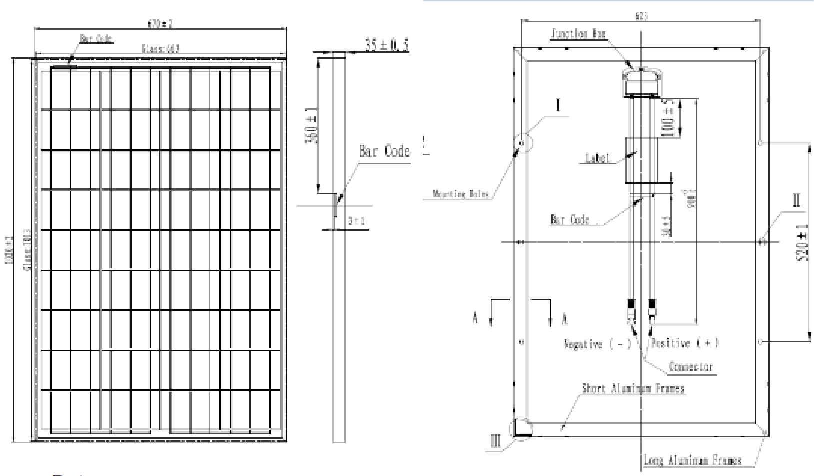
## MODEL: GS-STAR-100W

**Electrical Specifications**
(STC* = 25 °C, 1000W/m$^2$ Irradiance and AM=1.5)

| Model | GS-STAR-100W |
|---|---|
| Max system voltage (IEC/UL) | 1000V/600V |
| Maximum Power $P_{max}$ | 100 W* (0%, +6%) |
| Cell type | Poly silicon |
| Voltage at Maximum Power Point $V_{mpp}$ | 18.0 V |
| Current at Maximum Power Point $I_{mpp}$ | 5.56 A |
| Open Circuit Voltage $V_{oc}$ | 21.9 V |
| Short Circuit Current $I_{sc}$ | 6.13 A |
| Module Efficiency (%) | 14.63% |
| Temperature Coefficient of $V_{oc}$ | -0.32% /ºC |
| Temperature Coefficient of $I_{sc}$ | +0.04% /ºC |
| Temperature Coefficient of $P_{max}$ | -0.45% /ºC |

*Standard Test Conditions

**Physical Specifications mm**




**Other Performance Data**

| Power Tolerance | Operating Temperature | Max Series Fuse Rating | NOCT* |
|---|---|---|---|
| 0%, +6% | -40 ºC to +85 ºC | 10A | 45 +/-2ºC |

*Normal Operating Cell Temperature

**www.GrapeSolar.com**
**For service or support call**
**1-541-349-9000**

2635 W. 7th Place
Eugene, Oregon 97402, USA
Tel: 541.349.9000 Fax: 541.343.9000

Grape Solar reserves the rights to modify these specifications without notice.

Rev.02• 1611

**McMASTER-CARR.**

## Multipurpose 6061 Aluminum Sheet

**0.016" Thick, 48" x 48"**

$88.33 Each
89015K126

| | |
|---|---|
| Material | 6061 Aluminum |
| Shape | Sheet and Bar |
| Thickness | 0.016" |
| Thickness Tolerance | -0.002" to 0.002" |
| Tolerance Rating | Standard |
| Width | 48" |
| Width Tolerance Range | -1/16" to 1/16" |
| Length | 48" |
| Length Tolerance | -1/8" to 1/8" |
| Yield Strength | 35,000 psi |
| Fabrication | Cold Rolled |
| Temper | T6 |
| Heat Treatment | Hardened |
| Hardness | Brinell 95 |
| Hardness Rating | Soft |
| Heat Treatable | Yes |
| Appearance | Plain |
| Temperature Range | -320° to 300° F |
| Specifications Met | AMS 4027, ASTM B209 |
| Aluminum Performance Properties | Corrosion Resistant, Easy to Machine, Easy to Weld |
| Flatness Tolerance | Not Rated |
| Elongation | 12.5% |
| Material Composition | |
| Aluminum | 95.1-98.2% |
| Chromium | 0.4-0.8% |
| Copper | 0.05-0.4% |
| Iron | 0-0.7% |
| Magnesium | 0.8-1.2% |
| Manganese | 0-0.15% |
| Nickel | 0-0.05% |
| Silicon | 0.4-0.8% |
| Titanium | 0-0.15% |
| Zinc | 0-0.25% |
| Zirconium | 0-0.25% |
| Other | 0.15% |
| Warning Message | Physical and mechanical properties are not guaranteed. They are intended only as a basis for comparison and not for design purposes. |
| RoHS | RoHS 3 (2015/863/EU) Compliant |
| REACH | REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant |
| Country of Origin | Varies |

The most widely used aluminum, 6061 is fabricated into everything from pipe fittings and containers to automotive and aerospace parts. It is

McMASTER-CARR.

## Multipurpose 6061 Aluminum

**10" Diameter**

1610T68

| | |
|---|---|
| Material | 6061 Aluminum |
| Shape | Rod and Disc |
| Diameter | 10" |
| Diameter Tolerance | -0.104" to 0.104" |
| Tolerance Rating | Standard |
| Length Tolerance | -0.015" to 1/8" |
| Yield Strength | 35,000 psi |
| Fabrication | Extruded |
| Temper | T6 |
| Heat Treatment | Hardened |
| Hardness | Brinell 95 |
| Hardness Rating | Soft |
| Heat Treatable | Yes |
| Appearance | Plain |
| Temperature Range | -320° to 300° F |
| Specifications Met | ASTM B221 |
| Aluminum Performance Properties | Corrosion Resistant, Easy to Machine, Easy to Weld |
| Straightness Tolerance | Not Rated |
| Elongation | 12.5% |
| Material Composition | |
| Aluminum | 96-98.61% |
| Chromium | 0.04-0.35% |
| Copper | 0.15-0.4% |
| Iron | 0-0.7% |
| Magnesium | 0.8-1.2% |
| Manganese | 0-0.15% |
| Silicon | 0.4-0.8% |
| Titanium | 0-0.15% |
| Zinc | 0-0.25% |
| Warning Message | Physical and mechanical properties are not guaranteed. They are intended only as a basis for comparison and not for design purposes. |
| Length | 1/2 in., 1 in., 3 in. |
| RoHS | RoHS 3 (2015/863/EU) noncompliant |

The most widely used aluminum, 6061 is fabricated into everything from pipe fittings and containers to automotive and aerospace parts. It is strong and corrosion resistant, plus it's easy to machine and weld.

McMASTER-CARR.

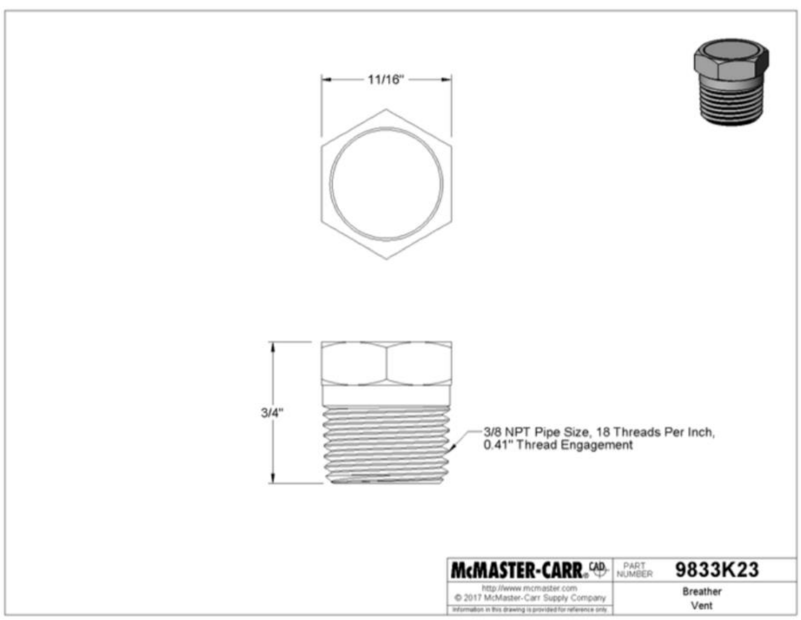
## Breather Vent

**Nickel-Plated Steel, 3/8 NPT Male**

$2.44 Each
9833K23

| | |
|---|---|
| Style | A |
| Connection Type | Pipe |
| Pipe Connection Type | Threaded |
| Pipe Size | 3/8 |
| Thread Type | NPT |
| Gender | Male |
| Maximum Flow Rate | 7 scfm @ 100 psi |
| Maximum Pressure | 150 psi |
| Maximum Temperature | 300° F |
| Height | 3/4" |
| Drive Style | External Hex |
| Hex Size | 11/16" |
| For Use With | Air, Inert Gas |
| Material | |
| Body | Nickel-Plated Steel |
| Fitting | Nickel-Plated Steel |
| Filter | Bronze |
| Filter Construction | Porous |
| For Reducing | Particles |
| Removes Particle Size Down To | 90 microns |
| RoHS | RoHS 3 (2015/863/EU) compliant with exemption 6(a)-I - Lead as an alloying element in steel |
| REACH | Not Compliant |
| Country of Origin | United States |

Protect against excess vacuum and pressure in cylinders, gear boxes, enclosures, manifolds, and tanks. You can also use these breather vents to block debris from entering equipment.



**McMASTER-CARR.**

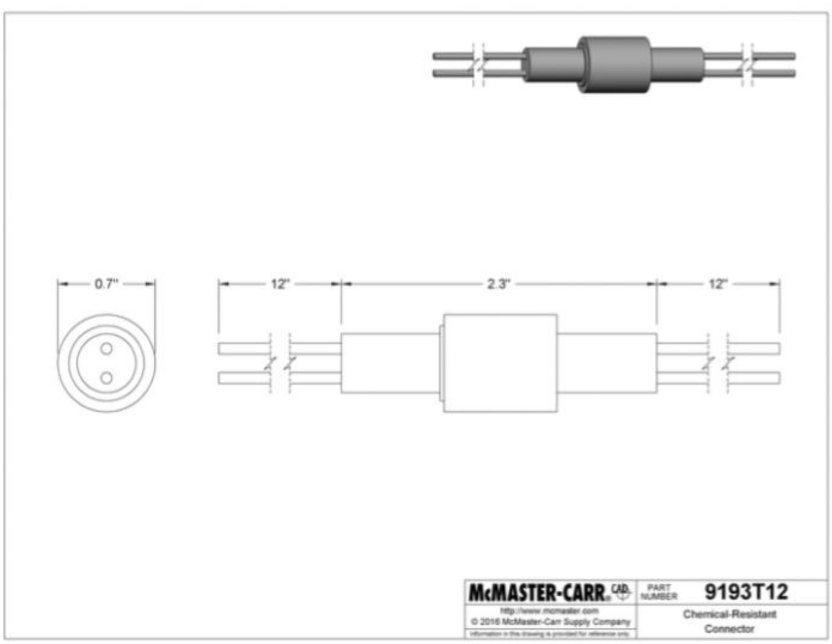
## Chemical-Resistant Push-In Connector Set

**2 Poles, 15 Amps**

$17.27 Each
9193T12

| | |
|---|---|
| Application | Power/Signal |
| Connection Type | Pin |
| Housing Connection Type | Push In |
| Type | Straight Male Plug × Straight Female Socket |
| Number of Poles | 2 |
| Voltage | 400V AC/400V DC |
| Current | 15A |
| Wire Connection Type | Wire Leads |
| Wire Lead Gauge | 18 |
| Wire Lead Length | 12" |
| Wire Insulation Material | PVC Plastic |
| Wire Lead Color | Black, White |
| Color | Black |
| Housing Material | PVC Plastic |
| Mated Housing | |
| Diameter | 0.7" |
| Length | 2.3" |
| Pin Material | Tin-Plated Copper |
| Sleeve Material | Tin-Plated Copper |
| Temperature Range | -40° to 220° F |
| Environment | Corrosive, Oily, Outdoor, Washdown |
| Environmental Rating | IP67 |
| RoHS | Not Compliant |
| REACH | REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant |
| Country of Origin | United States |

With a PVC housing, connectors withstand exposure to chemicals, oil, fuel, and salt water. Each set includes one plug and one socket. They're often used in construction vehicles and machine tool applications. All come assembled with wire leads already installed so they can be quickly added to existing wiring systems. When mated, connectors meet IP67 for protection against washdowns.




The information in this 3-D model is provided for reference only.

McMASTER-CARR

## Fiberglass Insulation Sheet

**2" Thick x 48" Wide x 10 Feet Long**

$40.08 Each
9346K38

| | |
|---|---|
| For Use On | Enclosures and Equipment |
| Insulation Type | Sheet/Strip |
| Backing Type | Plain |
| Thickness | 2" |
| Width | 48" |
| Length | 10 ft. |
| Temperature Range | 0° to 350° F |
| R Value | 7.7 |
| Heat Flow Rate | 0.26 Btu @ 75° F |
| Density | 0.95 lbs./cu. ft. |
| Material | Fiberglass |
| Color | Yellow |
| Flexibility | Flexible |
| Specifications Met | ASTM E84 25/50 for Flame and Smoke |
| Additional Specifications | SDS |
| RoHS | RoHS 3 (2015/863/EU) Compliant |
| REACH | REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant |
| Country of Origin | United States |

These lightweight, flexible fiberglass sheets are typically used to insulate equipment and appliances.

Sheets with temperature range of 0° to 350° F can be layered to increase efficiency.

McMASTER-CARR.

## Mirror-Like Multipurpose 110 Copper Wire

**1/4 lb. Spool, 0.020" Diameter**

$6.87 Each
8873K22

| | |
|---|---|
| Material | 110 Copper |
| Shape | Wire |
| Appearance | Mirror-Like |
| Diameter | 0.02" |
| Diameter Tolerance | -0.0004" to 0.0004" |
| Tolerance Rating | Standard |
| Yield Strength | Not Rated |
| Tensile Strength | 29,000 psi |
| Temper | Not Rated |
| Temper Rating | Softened (Annealed) |
| Hardness | Not Rated |
| Hardness Rating | Not Rated |
| Heat Treatable | No |
| Mechanical Finish | Polished |
| Specifications Met | ASTM B3 |
| Container Type | Spool |
| Container Size | 1/4 lbs. |
| Warning Message | Physical and mechanical properties are not guaranteed. They are intended only as a basis for comparison and not for design purposes. |
| Length | 195 ft. |
| Additional Specifications | Wire Gauge Conversion Chart |
| RoHS | RoHS 3 (2015/863/EU) Compliant |
| REACH | REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant |
| Country of Origin | United States |

This wire is polished to a mirror-like finish. Offering high electrical conductivity and formability, 110 copper is 99.9% pure. Also known as ETP copper, it's often used as grounding wire. It has a soft temper and will stay in place when bent.

# 14 Appendix F: Detailed Supporting Analysis

The following pages in Appendix F detail the heat transfer calculations made for this design.

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PROBLEM STATEMENT:

WE NEED TO DESIGN A SYSTEM WHICH STORES ENOUGH HEAT TO BE USED AS A MEANS OF COOKING A MEAL. ADDITIONALLY, IT SHOULD DIRECT A MAJORITY OF THIS HEAT THROUGH THE FOOD (IN ORDER TO COOK IT).

INITIAL SIZING ANALYSIS:

TO DETERMINE THE ENERGY REQUIRED WE'LL ASSUME AN EXAMPLE MEAL OF SOUP IS BEING COOKED:

6" e-stove burner ≅ 1200 watts

soup ≅ 30 min cook time

$\therefore P_{req} = (1200 \text{ J/sec (watts)})(30 \text{ min}) \cdot \left(\frac{60 \text{ sec}}{1 \text{ min}}\right)$

$\boxed{P_{req} = 2.16 \text{ MJ}}$

ENERGY STORED IN ERITHRYTOL:

$\therefore Q_{stored} = m(T_H c_{p_\ell} - T_L c_{p_s} + h_{melt})$

$\boxed{m(2.16 \text{ MJ}) = 2.7 \text{ kg}}$

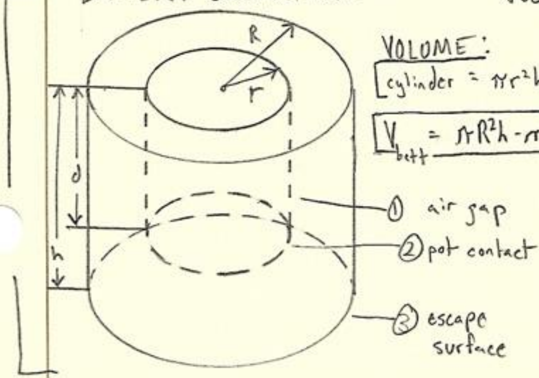
$T_H = 413.15$ [K] (140°C)
$T_L = 293.15$ [K] (20°C)
$c_{p_\ell} = 2.76$ [kJ/kg K]
$c_{p_s} = 1.38$ [kJ/kg K]
$h_{melt} = 340$ kJ/kg

HERE'S A TABLE:

| # OF MEALS | MASS OF PCM (kg) | DENSITY | VOLUME (cm³) |
|---|---|---|---|
| 1 | 2.7 | $\rho_s = 1.48$ g/cm³ | 1 - 1,824 |
| 2 | 5.4 | $\rho_\ell = 1.30$ g/cm³ | 2 - 3,648 |
| 3 | 8.1 | | 3 - 5,472 |
| 4 | 10.8 | | 4 - 7,296 |
| 5 | 13.5 | | 5 - 9,120 |

$\left(\frac{1 \text{ kg}}{1000 \text{ g}}\right)$ conversion factor

BATTERY GEOMETRY:




VOLUME:

cylinder $= \pi r^2 h$

$\boxed{V_{batt} = \pi R^2 h - \pi r^2 d}$

SURFACE AREA:

circle $= \pi r^2$
cylinder wall $= 2\pi r h$

$SA_1 = 2\pi r d$

$SA_2 = \pi r^2$

$SA_3 = 2\pi R^2 + 2\pi R h - \pi r^2$ ($SA_2$)

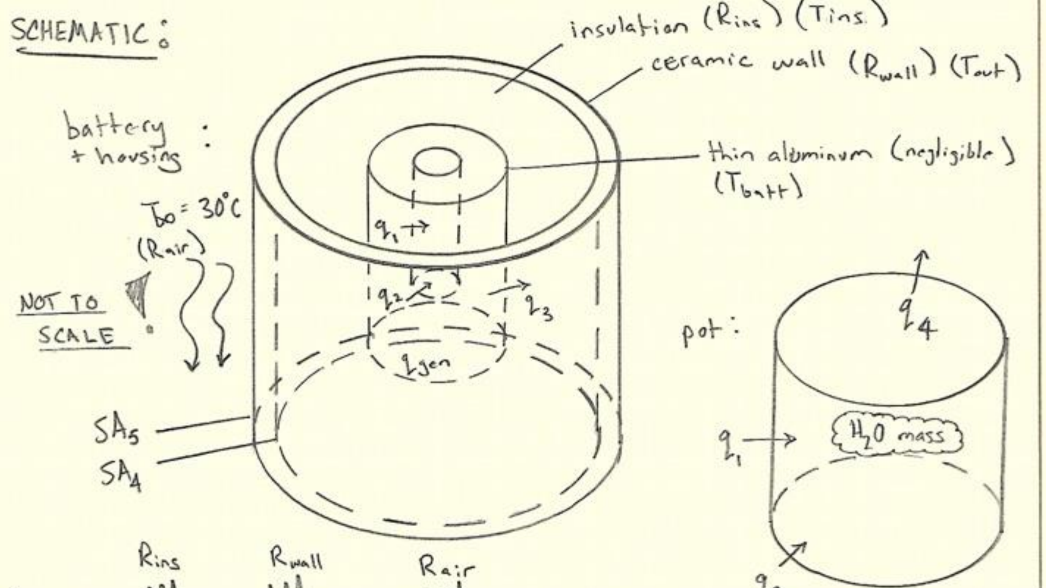
## HEAT TRANSFER ANALYSIS:

IN ORDER TO PERFORM ANALYSIS, WE WILL CONSIDER THE ISEC IN SEVERAL STATE CONDITIONS:

1- HOUSING W/ BATT @ 140°C ← STRAY HEAT MODEL
2- POT @ 15°C ← INITIAL LOAD OPERATION MODEL
3- POT @ 100°C ← STEADY STATE OPERATION MODEL

- OUR SYSTEM IS TOO COMPLEX TO BE MODELED W/ THE LUMPED CAPACITANCE METHOD & TRANSIENT ANALYSIS WOULD REQUIRE TOO MANY NODES TO BE ACCOUNTED FOR.
- INSTEAD, BY PERFORMING STATE ANALYSIS, WE CAN "UNFOLD" OUR BATTERY & ANALYZE THE SYSTEM WITH 1-D HEAT TRANSFER.

SCHEMATIC:



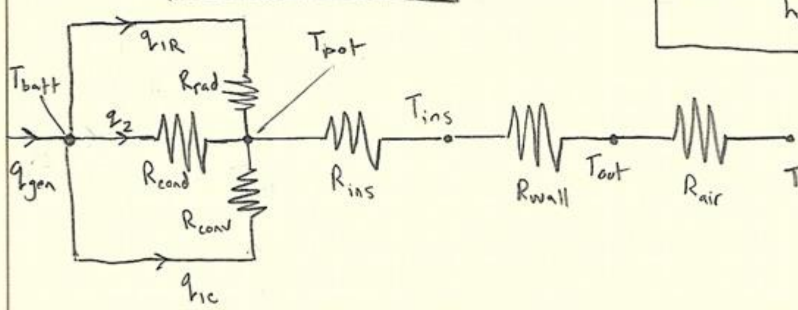

$q_3$ → $T_{batt}$ — $R_{ins}$ — $T_{ins}$ — $R_{wall}$ — $T_{out}$ — $R_{air}$ — $T_\infty$

$$q_3 = \frac{T_{batt} - T_\infty}{R_{ins} + R_{wall} + R_{air}}$$

$$R_{ins} = \frac{\Delta x_{ins}}{K_{ins}\, SA_3} \quad \left[\frac{K}{W}\right]$$

$$R_{wall} = \frac{\Delta x_{wall}}{K_{wall}\, SA_4} \text{ — inside of housing}$$

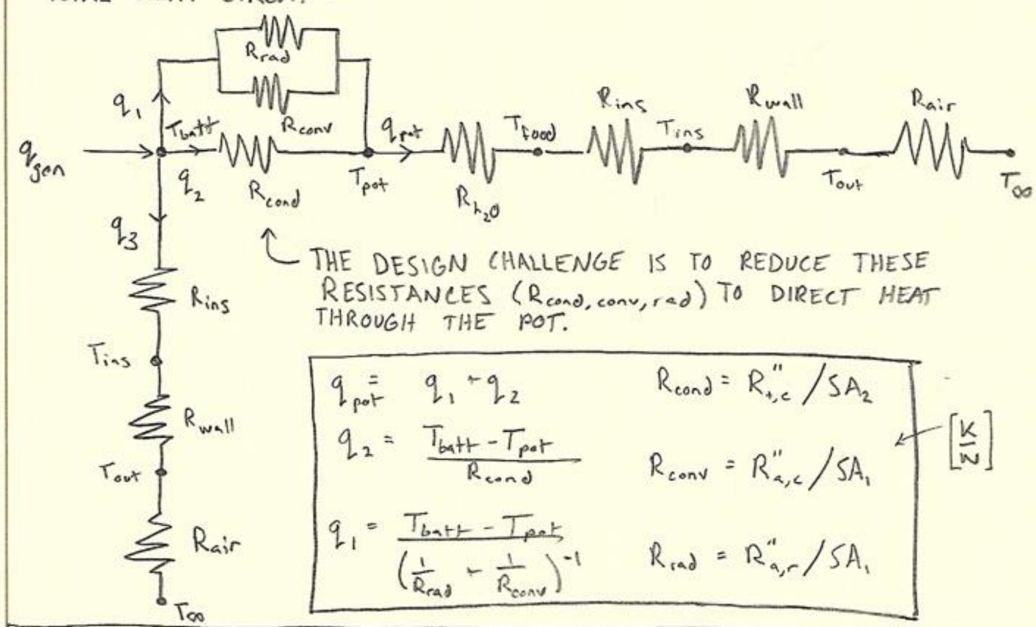
$$R_{air} = \frac{1}{h_{air}\, SA_5} \text{ — outside of housing}$$



3/5

## HEAT TRANSFER ANALYSIS (cont.):

TOTAL HEAT CIRCUIT:




THE DESIGN CHALLENGE IS TO REDUCE THESE RESISTANCES ($R_{cond, conv, rad}$) TO DIRECT HEAT THROUGH THE POT.

$$q_{pot} = q_1 + q_2 \qquad R_{cond} = R''_{t,c} / SA_2$$

$$q_2 = \frac{T_{batt} - T_{pot}}{R_{cond}} \qquad R_{conv} = R''_{a,c} / SA_1$$

$$q_1 = \frac{T_{batt} - T_{pot}}{\left(\frac{1}{R_{rad}} + \frac{1}{R_{conv}}\right)^{-1}} \qquad R_{rad} = R''_{a,r} / SA_1$$

$\leftarrow \left[\frac{K}{W}\right]$

$\left[\frac{m^2K}{W}\right]$

$R''_{T,c} = 1.5$
$R''_{a,c} = 2.75$ } from tbl. 3.1 (pg 106) of Heat Transfer textbook

$$R''_{a,r} = \frac{\left(1/\varepsilon_{batt} + 1/\varepsilon_{pot} - 1\right)}{\sigma (T_{batt}+T_{pot})(T_{batt}^2+T_{pot}^2)}$$

Stefan-Boltzmann constant:
$\therefore \sigma = 5.67e{-8} \ \frac{W}{m^2K^4}$
$\therefore \varepsilon_{batt} = \varepsilon_{pot} \approx 0.77$
↳ engineering toolbox

## CRITICAL HEAT TRANSFER NOTES:

THIS DESIGN CAN BE IMPROVED BY INCREASING EMISSIVITY OF THE POT & THE HEATING SURFACES OF THE BATTERY. IT MAY ALSO BE IMPROVED THROUGH THE USE OF THERMAL GREASE OR CONTACT FILLER ON THE BOTTOM OF THE POT.

IN THIS ANALYSIS WE WILL ASSUME ANODIZED ALUMINUM TO MAXIMIZE $\varepsilon$ (EMISSIVITY), WHICH WILL MINIMIZE $R_{rad}$. ANODIZING THE ALUMINUM WILL BE A MAJOR MANUFACTURING STEP.

IT IS ALSO AN IMPORTANT MANUFACTURING CONSIDERATION TO HAVE A SMOOTHNESS TOLERANCE ON $SA_2$ TO MINIMIZE CONTACT RESISTANCE ($R_{cond}$).

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## EXPANSION & PRESSURE ANALYSIS:

EXPANSION TABLE:

| # OF MEALS | $MASS_{PCM}$ [kg] | (MAX) VOLUME [cm³] | ΔV [cm³] | Δ PRESSURE [Pa] |
|---|---|---|---|---|
| 1 | 2.7 | 1,824 | 253 | -440 |
| 2 | 5.4 | 3,648 | 505 | |
| 3 | 8.1 | 5,473 ~.5 gal | 758 | |
| 4 | 10.8 | 7,297 | 1,010 | |
| 5 | 13.5 | 9,121 | 1,262 | |
| 6 | 16.2 | 10,946 ~2.5 gal | 1,515 | |
| 7 | 18.9 | 12,770 | 1,768 | |
| 8 | 21.6 | 14,594 | 2,020 | |
| 9 | 24.3 | 16,419 ~4.8 gal | 2,273 | |
| 10 | 27 | 18,243 | 2,526 | |

NOTE: MAX PRESSURE IS CALCULATED BY TAKING (ΔV)(1.5) & USING THIS VOLUME AS AIR UNDER THE IDEAL GAS LAW:

$$\therefore P = nRT/V \longrightarrow \Delta P = \frac{\Delta n R \Delta T}{V}$$

$\rho_{air} = 1.204 \frac{kg}{m^3}$ @ 20 °C

$= 0.8338 \frac{kg}{m^3}$ @ 140 °C

$MM_{air} = 28.96$ kg/mol

$R = 287.05 \frac{J}{mol K}$

$$\therefore \Delta P = \frac{\left(\frac{(\rho_{air_{140}} - \rho_{air_{15}})^{*}V_{exp}}{MM_{air}}\right) R \left(T_H - T_L\right)}{^{*}V_{exp}}$$

$$\frac{\frac{\frac{kg}{m^3} \cdot cm^3 \cdot \left(\frac{1 m^3}{1e6\, cm^3}\right)^{*}}{kg/mol} \cdot \frac{J}{mol K} \cdot K}{cm^3 \cdot \left(\frac{1 m^3}{1e6\, cm^3}\right)^{*}}$$

$\frac{J}{m^3} \rightarrow$ SI base unit Pa

DON'T FORGET *CONVERSION FACTORS!

SEEMS LIKE THE BATTERY WILL EXPERIENCE PRESSURE CYCLES... A BREATHER VENT WILL ENHANCE THE LONGEVITY.

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MATLAB VERIFICATION:

$$\therefore\ m_{pcm} = V_{batt} \cdot \rho_{pcm} \cdot \left(\frac{1\,kg}{1e3\,g}\right) \cdot \frac{1e6\,cm^3}{1\,m^3} = [kg]$$

($V_{batt}$ in $m^3$, $\rho_{pcm}$ in $g/cm^3$)

$$\therefore\ \Delta V = \left[m_{pcm} \div (\rho_{pcm_s}) - m_{pcm} \div (\rho_{pcm_l})\right] \cdot \frac{1e3\,g}{1\,kg}$$

($m_{pcm}$ in kg, $\rho$ as $cm^3/g$)

$$\therefore\ m_{pcm\,fill} = m_{pcm} - \Delta V(\rho_s) \cdot \frac{1\,kg}{1e3\,g}$$

($m_{pcm}$ in kg, $\Delta V$ in $cm^3$, $\rho_s$ in $g/cm^3$)

$$q_{pot} = \frac{T_{batt} - T_\infty}{\left(\frac{1}{R_{cond}} + \left(\frac{1}{R_{conv}} + \frac{1}{R_{rad}}\right)^{-1}\right)^{-1} + R_{H_2O} + R_{ins} + R_{wall} + R_{air}} \leftarrow SS$$

The following pages show the calculations run through MATLAB and its results.



**Contents**


- I.S.E.C. DESIGN CALCULATOR
- GEOMETRY INPUTS
- GEOMTRY CALCULATIONS
- PHASE CHANGE MATERIAL
- HEAT TRANSFER STOVE
- PRESSURE


## I.S.E.C. DESIGN CALCULATOR

Property of the Interdisciplinary Engineering ISEC Team at California Polytechnic State University.

Ahmed Gouda, Caroline Hodes, Paige Camacho, Wyatt Johnson

DESCRIPTION: This calculator is designed to rapidly calulate geometric design and heat transfer quantities specifically for the Insulated Solar Electric Cooker. This calculator serves as a tool to rapidly prototype estimates due to redesign withfdout prototype manufacturing.

The calculator is based off a cylidrical geometry. All values rough estimates, see logbook for engineering assumptions.

```
clc; clear all;
```

## GEOMETRY INPUTS

```
meters = .0254;                        % this is the inch/meter conversion
feet   = 3.28084;                      % this is the meter/foot conversion

r_batt_i    = 4.75 *meters;             % internal radius of battery's anchor [m]
d           = 6.75 *meters;             % depth of battery's anchor [m]
r_batt_o    = 6 *meters;                % external radius of battery [m]
h_batt      = 10 *meters;               % height of battery [m]
x_ins       = 12*meters;  %(4in)        % thickness of insulation [m]
x_wall      = 2 *meters;                % thickness of wall [m]
```

## GEOMTRY CALCULATIONS

```
%ADD TOTAL WEIGHT

r_wall_i    = (r_batt_o) + (x_ins);    % internal radius of the cooker wall
r_wall_o    = (r_wall_i) + (x_wall);   % external radius of the cooker wall
h_i         = h_batt + (2*x_ins);      % height inside the cooker walls [m]
h_o         = h_i + (2*x_wall);        % height of the entire cooker [m]

total_height_ft = h_o*(feet)                         % human factor measurements [ft]
total_width_ft  = (2*r_wall_o) * (feet)              % human factor measurements [ft]

V_anchor    = pi*(r_batt_i)^2*d;                                            % volume of the pot/anchor [m^3]
V_batt      = pi*(r_batt_o)^2*h_batt - V_anchor;                            % volume of the battery [m^3]

%SA_anchor   = 2*pi*(r_batt_i)*(d)         +   pi*(r_batt_i)^2;              % surface area of the battery anchor [m^2]
SA_1        = 2*pi*(r_batt_i)*(d);                                          % surface area of anchor air gap [m^2]
SA_2        =                                 pi*(r_batt_i)^2;              % surface area of anchor surface [m^2]
SA_escape   = 2*pi*(r_batt_o)*(h_batt)     + 2*pi*(r_batt_o)^2    - pi*(r_batt_i)^2;   % surface area of the battery case [m^2]
SA_inside   = 2*pi*(r_wall_i)*(h_i)        + 2*pi*(r_wall_i)^2;             % surface area on the inside of the stove [m^2]
SA_touch    = 2*pi*(r_wall_o)*(h_o)        + 2*pi*(r_wall_o)^2;             % surface area on the outside of the stove [m^2]

V_ins       = pi*(r_wall_i)^2*(h_i)        - (V_batt + V_anchor);        % volume of the insulation area [m^3]
V_wall      = pi*(r_wall_o)^2*(h_o)        - (V_ins + V_batt + V_anchor); % volume of the ceramic wall
```

```
total_height_ft =

    3.1667


total_width_ft =

    3.3333
```

## PHASE CHANGE MATERIAL

All data below listed is for erythritol

```
h_melt      = 340;          % heat of fusion (phase change enthalpy) for erythritol [kJ/kg]
h_vaporize  = 2465.4;       % heat of vaporization (phase change enthalpy) for H2O [kJ/kg]
rho_h2o     = 997;          % density of water as a liquid [kg/m^3]
rho_pcm_s   = 1.480;        % density of erythritol as a solild @ 20C [g/cm^3]
rho_pcm_l   = 1.300;        % density of erythritol as a liquid @ 140C [g/cm^3]
c_h2o       = 4;            % specific heat of water averaged between 15-100C [kJ/kgK]
c_s         = 1.38;         % specific heat of solid erythritol [kJ/kgK]
```

```
c_l         = 2.76;         % specific heat of liquid erythritol [kJ/kgK]
T_low       = 293.15;          % temp of solid erythritol [K]
T_high      = 413.15;          % temp of liquid erythritol [K]
T_h2o_init  = 15;           % temp of water initially in pot [C]
T_h2o_boil  = 100;          % temp of boiling water [C]
T_h2o_init_a  = 15 + 273.15;          % absolute temp of water initially in pot [K]
T_h2o_boil_a  = 100 + 273.15;         % absolute temp of boiling water [K]

m_pcm          = V_batt*rho_pcm_s*1e6*(1/1e3);                         % mass of erythritol in battery [kg]
PCM_expand_cm  = (m_pcm/(rho_pcm_l*1e-3)) - (m_pcm/(rho_pcm_s*1e-3))  % expansion of erythritol with heat cycle [cm^3]
m_pcm_fill_kg  = m_pcm-(PCM_expand_cm*rho_pcm_s*1e-3)                 % mass of erythritol to fill battery with [kg]
m_h2o          = V_anchor*rho_h2o;                                     % mass of water in the pot

Energy_Stored  = m_pcm_fill_kg * (T_high*c_l - T_low*c_s + h_melt)    % energy stored in battery [kJ]
Boil_init      = m_h2o*(c_h2o*(T_h2o_boil-T_h2o_init))                % energy needed to bring water to boiling temp [kJ]
Boil_full      = m_h2o*(h_vaporize)                                    % energy needed to fully boil water [kJ]
```

```
PCM_expand_cm =

   1.4806e+03


m_pcm_fill_kg =

   13.6342


Energy_Stored =

   1.4667e+04


Boil_init =

   2.6578e+03


Boil_full =

   1.9272e+04
```

### HEAT TRANSFER STOVE

```
T_atm   = 30;       % atmospheric temperature for Ghana [C]
T_batt  = 140;      % max operating temperature [C]
T_h2o   = 15;       % amtospheric temperature of water in Ghana [C]
k_ins   = .0525;    % thermal conductivity for insulation [W/mK]
k_wall  = 0.8;      % thermal conductivity for ceramic [W/mK]
h_air   = 10;       % convection coefficient for air [W/m^2K]
h_h2o   = 20;       % convection coefficient for h20 [W/m^2K]
sb_c    = 5.67e-8;  % Stefan Boltzmann constant [W/m^2K^4]
emis    = 0.77;     % emissivity coefficient for anodized aluminum

R_al_al     = 1.5;                                                       % contact    resistance for aluminum on aluminum                      [m^2*
R_al_air_c  = 2.75;                                                      % convection resistance for air on aluminum                           [m^2*
R_al_air_r  = ((1/emis)+(1/emis)-1)/(sb_c*(T_high-T_h2o_init_a)*(T_high^2-T_h2o_init_a^2));     % radiation  resistance for anodized aluminum on anodized aluminum [
R_al_air_r_ss  = ((1/emis)+(1/emis)-1)/(sb_c*(T_high-T_h2o_boil_a)*(T_high^2-T_h2o_boil_a^2));  % radiation  resistance for anodized aluminum on anodized aluminum [

R_ins   = (x_ins)/(k_ins*SA_escape);        % thermal resistivity of the insulation [K/W]
R_wall  = (x_wall)/(k_wall*SA_inside);      % thermal resistivity of the stove wall [K/W]
R_air   = 1/(h_air*SA_touch);               % thermal resistivity of the air [K/W]

R_h2o   = 1/(h_h2o*(SA_1+SA_2));            % thermal resistivity of the water [K/W]

R_cond  = R_al_al       / SA_2;             % resistance to conduction through anchor [K/W]
R_conv  = R_al_air_c    / SA_1;             % resistance to convection through air gap [K/W]
R_rad   = R_al_air_r    / SA_1;             % resistance to radiation through air gap [K/W]
R_rad_ss = R_al_air_r_ss / SA_1;             % resistance to radiation through air gap at steady state [K/W]

R_anchor_eq    = ((1/R_cond)+(1/((1/R_conv)+(1/R_rad))^-1))^-1;
R_anchor_eq_ss = ((1/R_cond)+(1/((1/R_conv)+(1/R_rad_ss))^-1))^-1;

q_esc        = (T_batt-T_atm)/(R_ins+R_wall+R_air)     % heat transfer stray [W/m^2]

q_pot        = (T_batt-T_h2o)/(R_anchor_eq+R_h2o)                 % heat transfer to initial load [W/m^2]
q_pot_stable = (T_batt-T_atm)/(R_anchor_eq_ss+R_h2o+R_wall+R_air)  % heat transfer through load at equilibrium [W/m^2]

T_wall_gain  = T_atm + q_esc*(R_ins*R_wall)                 % temperature on outside surface of ISEC [C]
```

```
q_esc =

    6.4922


q_pot =
```

```
    15.4727


q_pot_stable =

     8.9496


T_wall_gain =

    31.8368
```

## PRESSURE

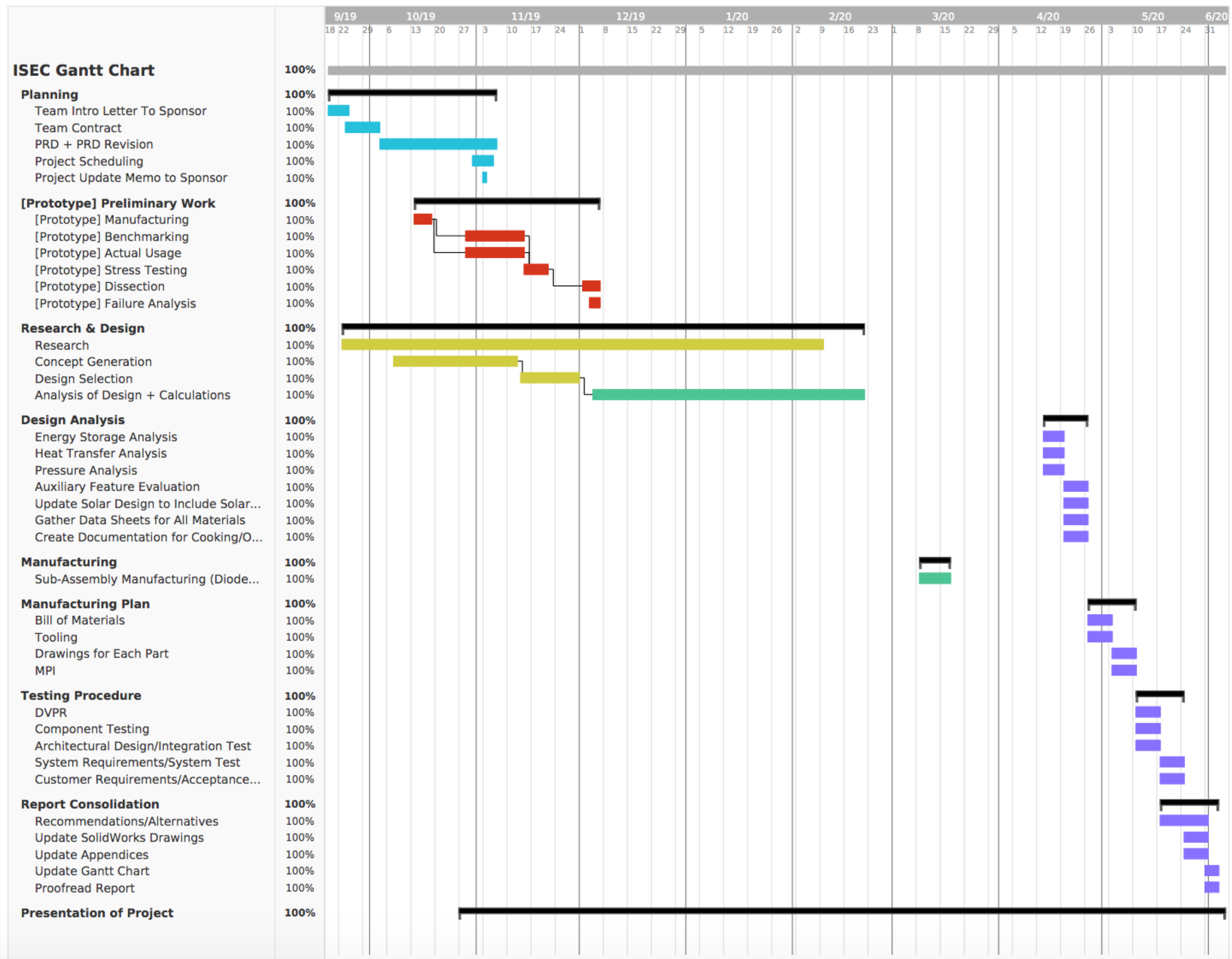
```
V_air    = PCM_expand_cm*1.5;        % the space which is left empty to provide for PCM expansion [m^3]
MM_air   = 28.9647;                  % the molar mass of air [kg/mol]
rho_air = 1.225;                     % the density of air at 25degC [kg/m^3]
rho_air_c    = 1.204;                % density of air at 20C [kg/m^3]
rho_air_h    = 0.8338;               % density of air at 140C [kg/m^3]
T_air    = 20;                       % the temperature of air [C]
GC_air   = 287.05;                   % the R (gas constant) for air [J/kg*K]
n_air_c    = (V_air*rho_air_c)/MM_air;   % the # of moles while cold []
n_air_h    = (V_air*rho_air_h)/MM_air;   % the # of moles while hot []

delta_pressure = ((n_air_c-n_air_h)*GC_air*(T_batt-T_air))/ V_air     % pressure produced within the battery []
```

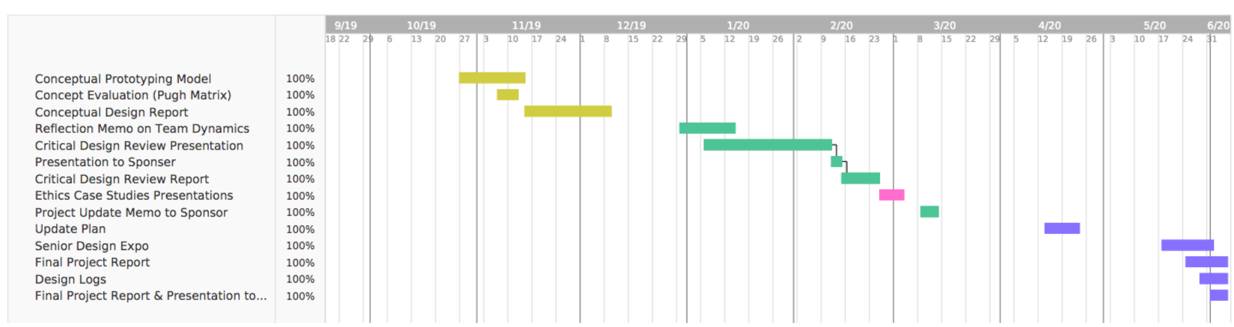
```
delta_pressure =

   440.2569
```

*Published with MATLAB® R2019a*

# 15 Appendix G: Gantt Chart

Appendix G shows the Gantt Chart for the project. The chart outlines the projected timeline and milestones for the project. The Gantt Chart was heavily modified and updated after the senior project class went virtual amid the pandemic.



# 16 Appendix H: Product Guide for User

## 16.1 Using the Sugar Oven

1. The local Sugar Oven installation technician will place the solar panel for optimum sunlight and help place the Sugar Oven within the home.
    a. Note that should the Sugar Oven ever need to be moved, multiple people will need to assist as the Sugar Oven will be very heavy.
2. Connect the power connector from the solar panel to the plug from the Sugar Oven in the house.
3. To cut of power to the Sugar Oven and stop heat from being produced, unplug the connector between the Sugar Oven and the solar panel.
    a. Do not try to disconnect from any other point along the Sugar Oven or solar panel and only disconnect at the connection point.
4. The Sugar Oven will take approximately 3 hours to heat up to 140°C.
    a. While there is a connector plug to allow for the ability to cut off power to the oven, the intention is to leave it on and running consistently so that the erythritol can absorb the heat throughout the day and be hot and ready when it is time to cook.

## 16.2 Safety Considerations

1. Fiberglass in between two exterior layers of insulation made of a perlite and fiberglass mixture.
2. The thermal battery which contains the heating elements of the system will not be exposed to users to avoid the risk of burns.
    a. The pot that fits into the thermal battery will also have handles along the side which are made for users to carry.
    b. For cleaning, the pot should be removed with heat-resistant gloves or cloth.
3. The thermal battery contains erythritol that expands as it melts, causing a large pressure differential within the battery.
    a. To deal with that, the thermal battery contains a breather vent along the top of the ISEC to release excess pressure if needed.
4. The ISEC is designed to stay in a fixed area and will have precautions that if it does need to get lifted, a group of people will be required to carry it.

## 16.3 Repair Considerations

1. Should the Sugar Oven stop heating food, repair can easily be addressed by swapping batteries of the subsystems.
    a. Each subsystem can be replaced under technician rework with quick field repairs being made on a component level. Depending on where the user is located, contact information for these technicians would be provided upon distribution.
    b. The diode chain has been the source of failure on previous models of the ISEC, so in this model, adjustments were made. These specific diodes were specifically chosen to work within their manufactured specification.
    c. The manufacturing of the diode chain has been streamlined to make sure the diodes are getting properly connected as to minimize risk of failure.
    d. The aluminum from the thermal battery can be reused for future ISECs, and all the other components of the system can be maintained for future use.
2. If the perlite concrete mixture insulation were to fail on the ISEC, a mold will be available to make another mixture at little cost and with relative ease.

# 17 Appendix I: Design Verification Plan and Report

*Table 6. DVPR.*

| Item No. | Clause Reference | Test Description | Acceptance Criteria | Quantity |
|---|---|---|---|---|
| Detailed Design and Concept Verification (Type A) | | | | |
| 1 | Heating Element | 20 Diodes, test how long it takes to get to temperature (140°C) while enclosed in an insulator (Fiberglass). Test by having a thermocouple on the body of the resistive heating assuming a uniform temperature along the element | Heat up to temperature in no longer than 3 hours with no failure would be considered a pass | 3 test samples |
| 2 | Phase Change Material | test melting temperature by putting thermocouples on inside of container carrying roughly same volume as the thermal battery will have. Record temperature of phase change and other set points using specific grade of erythritol | Find important points in temperature with erythritol, be able to use information for future desi | 3 test samples |
| 3 | Thermal Contact | test thermal connection between pot and thermal battery to see heat transfer. Have thermocouple on inside of pot filled with water as well as on outside cylinder of thermal battery. Test temperature difference against time, as well as time to boil water | Find thermal contact of pot. If takes longer than 3 hours to boil water, fail | 4 test samples |
| Architectural Design and Design Verification (Type B) | | | | |
| 4 | Heating Element | diodes at 3 Amps under 150°C along with phase change material (erythritol). Test how long it takes to get to temperature (140°C) while enclosed in aluminum thermal battery with insulator (Fiberglass). Test by having a thermocouple on the cylindrical body of the thermal battery assuming a uniform temperature along the battery. Also look for possible failures, although this was verified in previous studies. | Find if thermal battery reaches temperature properly, no longer than 3 hours with no failure would be considered a pass | 1 test sample |
| 5 | Thermal Battery | The purpose of this test is to validate the efficacy of the thermal battery sub-system of the ISEC. This test will be performed by testing time for pot interface of the thermal battery to reach 140°C with a thermocouple. One has reached 140°C, pour room temperature water into pot. Record time to boil water the entire system will be enclosed in fiberglass and attached to a solar panel as a power source. | Test to see the heat differential between the thermal battery and outside of insulation. | 1 test sample each treatment |
| System and Acceptance Test and Product Verification (Type C) | | | | |
| 6 | Sugar Oven | Test entire system: working with all components, including pot, test to see if cooker effectively cooks vegetables and stews commonly eaten in Ghana. Failure test, see if can effectively cook in a reasonable time without failure. | To see if there are any points of failure before acceptance test | 3 test samples each treatment |

# 18 Appendix J: Material Engineering Properties

The tables in Appendix J show the Material Engineering Properties for all elements mentioned in the design analysis verification.

*Table 7. Material Engineering Properties for Erythritol, Aluminum, Fiberglass Insulation, Perlite and Concrete Mixture, Air, and Water.*

| | |
|---|---|
| **Erythritol** | |
| Melting Temperature [$T_m$] | 120 [ºC] |
| Enthalpy [$h_m$] | 345 [J/g] |
| Specific Heat (solid) [$C_{p,s}$] | 1.38 [J/g*K] |
| Specific Heat (liquid) [$C_{p,l}$] | 2.76 [J/g*K] |
| Thermal Conductivity(solid) [$\lambda_s$] | 0.733 [W/m*K] |
| Thermal Conductivity (liquid) [$\lambda_l$] | 0.326 [W/m*K] |
| Density(solid) [$\rho_s$] | 1.48 [g/cm$^3$] |
| Density(liquid) [$\rho_l$] | 1.30 [g/cm$^3$] |
| **Aluminum** | |
| Thermal Conduct Resistance [$k_{al}$] | 1.50 [m$^2$*K/W] |
| Thermal Convection Resistance [$h_{al}$] | 2.75 [m$^2$*K/W] |
| **Insulation** | |
| Thermal Conductivity [$k_{ins}$] | 0.0525 [W/m*K] |
| **(20%) Pearlite (80%) Concrete Mixture** | |
| Thermal Conductivity [$k_{wall}$] | 0.8 [W/m*K] |
| **Air** | |
| Thermal Connectivity [$h_{air}$] | 10 [W/m$^2$K] |
| Density (20ºC) [$\rho_{air}$] | 1.225 [kg/m$^3$] |
| Density (25ºC) [$\rho_{air,c}$] | 1.204 [kg/m$^3$] |
| Density (140ºC) [$\rho_{air,h}$] | 0.8338 [kg/m$^3$] |
| Molar Mass [$MM_{air}$] | 28.965 [kg/mol] |
| Atmospheric Gas Constant [$GC_{air}$] | 287.05 [J/kg*K] |
| **$H_2O$** | |
| Thermal Connectivity [$h_{al}$] | 20 [m2*K/W] |

# 19 Appendix K: Safety Checklist

Table 8 shows the Safety Check List for the ISEC. As shown, each specification is indicated on the right. For certain items on the checklist, we have provided appropriate comments.

*Table 8. Safety Checklist.*

| Y | N | Checklist Item |
|---|---|---|
| ✓ | | Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?<br>**Comments**: pinch points when inserting stove |
| | ✓ | Can any of the design undergo high acceleration / decelerations? |
| | ✓ | Will the system have any large moving masses or large forces? |
| | ✓ | Will the system produce a projectile? |
| | ✓ | Would it be possible for the system to fall under gravity creating injury? |
| | ✓ | Will a user be exposed to overhanging weights as part of the design? |
| | ✓ | Will the system have sharp edges? |
| ✓ | | Will all the electrical systems be properly grounded? |
| | ✓ | Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC? |
| ✓ | | Will there be any stored energy in the system such as batteries, flywheels, hanging weights, or pressurized fluids?<br>**Comments**: pressurized fluids (erythritol) |
| ✓ | | Will there be any explosive or flammable liquids, gases, dust fuel part of the system?<br>**Comments**: insulation (fiberglass) |
| | ✓ | Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design? |
| | ✓ | Can the system generate high levels of noise? |
| ✓ | | Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.…?<br>**Comments**: high temperatures |
| ✓ | | Will the system be easier to use safely rather than unsafely? |
| ✓ | | Will there be any other potential hazards not listed above? If yes, please explain.<br>**Comments**: any user contact points could be extremely hot; moving the device could be a hazard because it is heavy |